A United States Contribution
to the International Hydrological Decade

HYDROLOGIC ENGINEERING METHODS
FOR WATER RESOURCES DEVELOPMENT

VOLUME 7
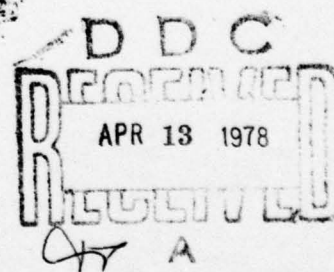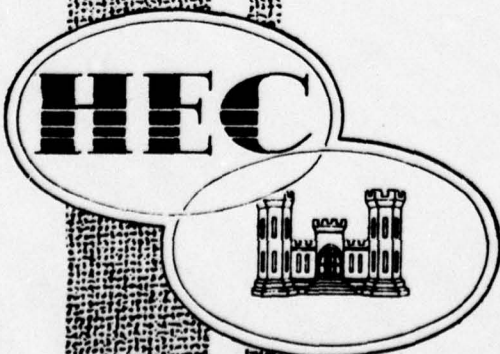
FLOOD CONTROL
BY RESERVOIRS

WITHOUT APPENDICES 1, 2, 3, 4, and 5

THE HYDROLOGIC ENGINEERING CENTER
CORPS OF ENGINEERS, U.S. ARMY
DAVIS, CALIFORNIA

FEBRUARY 1976

IHD 1965 1974

HYDROLOGIC ENGINEERING METHODS
FOR WATER RESOURCES DEVELOPMENT

VOLUME 7

FLOOD CONTROL BY RESERVOIRS

by

LEO R. BEARD

FEBRUARY 1976

FOREWORD

This volume is part of the 12-volume report entitled "Hydrologic Engineering Methods for Water Resources Development," prepared by The Hydrologic Engineering Center (HEC) as part of the U. S. Army Corps of Engineers' participation in the International Hydrological Decade. This volume discusses the basic principles that are applied in reservoir operation for flood control, and describes methods and procedures that are consistent with these principles. Emphasis is placed on selected practical methods and procedures for operating reservoirs for flood-control rather than on the underlying theory. Although many of the methods and procedures described herein have been used successfully by the Corps of Engineers, the volume should not be construed to re-present the official policy or criteria of the Corps.

This volume was prepared primarily by Leo R. Beard, HEC Director until July 1972. Messrs. Bill S. Eichert (present HEC Director), Edward F. Hawkins, James McHughes, John C. Peters, and Dale R. Burnett reviewed and provided valuable assistance in preparing this volume.

i

CONTENTS

CONTENTS

CONTENTS

CHAPTER 1. INTRODUCTION

Section 1.01. Purpose

The purposes of this volume are to present basic principles of
reservoir operation for flood control and to describe procedures for
establishing operational criteria. Topics include determination of
reservoir release rates, regulation of the reservoir design flood,
considerations for determining outlet and spillway regulation, deter-
mination of rule curves, and procedures for analyzing multiple-
reservoir operation. The applicability of computer simulation for
establishing operational criteria is discussed, and several computer
programs are described in the appendixes.

Section 1.02. Basic Principles

Basic principles applied in reservoir operation for flood control
are summarized briefly as follows:

_a_. The reservoir storage reserved for flood control should be
utilized in such a manner as to maximize benefits over the life-time
of the reservoir. For completed projects reservoir space allocated to
flood control should be utilized to assure the protection for which the
project was designed and upon which downstream interests have based
their developments.

<u>b</u>. Reduction in flood control space requirements can sometimes be made on the basis of seasonal variation in flood potential or, if long-term forecasts are dependable (as in the case of snowmelt floods in some regions), space can be adjusted in relation to the forecast.

<u>c</u>. Reservoir space provided for flood control should be held empty during times when full flood potential exists, except for temporary storage of flood waters to prevent downstream flooding.

<u>d</u>. Whenever water is stored in flood control space, releases should be made at maximum rates that do not cause substantial damage downstream, subject to limiting controls on the rate-of-change of release and subject to unforeseen emergency conditions.

<u>e</u>. Reduction in target release rates when the flood hazard is low is discouraged, because such intermittent protection encourages development in low areas that can inhibit important flood releases in the future.

<u>f</u>. Maintenance of channel capacities and proper management of flood plains downstream of reservoirs is especially important for maintaining reservoir release capability.

<u>g</u>. The operation of very large outlet gates and particularly the operation of spillway gates can be extremely hazardous and should be strictly regulated by the use of emergency release rules.

The methods and guides presented in the following chapters are intended to be consistent with these principles.

CHAPTER 2. CONTROLLED RESERVOIR RELEASES

Section 2.01. Release Considerations

As discussed in Volume 1, it is generally most economical and
effective to make maximum releases to empty flood storage consistent
with downstream conditions in order to minimize the need for valuable
reservoir flood control space. Maximum feasible target flows at any
downstream location are usually those that do not produce serious
flood damage by inundation. The stage (elevation) at which serious
damage begins can be determined from topographic map studies and field
inspections. The flow corresponding to this stage is determined from
a rating curve that can be constructed from observed flood stages and
flows. The maximum nondamaging flow can vary seasonally, for example
where damages are primarily agricultural. Where flow measurements are
not available, water surface profiles for various flows may be computed,
using methods described in Volume 6, and a stage-discharge curve can
then be contructed. The best information on water surface profiles
and inundated areas is that obtained during and immediately following
actual floods where the peak flow is known and high-water marks are
obtained along the damage reach.

If good observational data are not available for estimating
maximum flows that are not seriously damaging, it can often be inferred
that the flow exceeded in half of the years (i.e., the 2-year flood as
determined from a flow frequency study) is approximately the maximum

flow that is not seriously damaging. This is because those who are damaged soon learn to avoid frequent damage if it is serious. It should be noted, however, that reservoir control often reduces the frequency of such flows, and the tendency to use flood-prone areas unwisely must be controlled by regulations, particularly when the flood-control effectiveness of reservoirs depends on the availability of downstream channel capacity.

In a planning study in which the storage and release capacity and operation rules for a flood control reservoir are being determined, allowance must be made for imperfection in operation as discussed in Volume 1. Experience in the western United States has shown that for design purposes, the target flow at damage locations should be about 80 percent of the actual flow above which significant damages occur. Then, in actual operation, every effort should be made to utilize effectively all of the flow capacity. If this is done, the effectiveness of actual operation can reasonably approach the design objectives.

Where a reservoir is operated to regulate floods at locations a considerable distance downstream, allowance must be made for local runoff that will occur downstream of the dam and above the damage area. The release from the reservoir is determined as the difference between the target flow and the maximum local runoff forecasted to occur during the times when a portion of the current releases will reach the damage area. Maximum forecasted local runoff in the application is the "best forecast" amount plus a contingency allowance. This contingency allowance usually ranges from 25 to 100 percent of the local runoff during rain floods, because forecast accuracy for rapidly

changing flow is rather poor. The amount of contingency depends on the
consequences of exceeding target flows. If these are serious, as where
levees exist, the contingency allowance should be high in order to
avoid a preventable disaster.

The importance of coordinating releases to forecasted local inflows
at a downstream damage location depends to some extent on the relation
of flood control storage to release rate. Where storage is large and
the amount of water that can be released during the flood inflow period
is a small part of the design flood volume, it may not be worthwhile
to take an unnecessary chance of exceeding safe flows downstream. On
the other hand, where the release during floods is large and consti-
tutes a major part of the design flood volume, failure to make maximum
feasible releases during flood inflow periods could be disastrous.

Section 2.02. Use of Index Flows to Forecast Local Runoff

Experience has demonstrated that forecasts of runoff based on
measured rainfall are not highly dependable and that the use of fore-
casted rainfall for flood operations is subject to major uncertainty.
Where forecasts of local runoff downstream of a reservoir must be made
for release scheduling, it is usually best to use river-stage reports
from an index location within the local tributary area as an indicator
of the total runoff. If index-station flows at the time of a particular
reservoir release correlate with local runoff that reaches the damage
center as late or later than the reservoir release does, a relationship
between index flow and total local flow can be developed, along with

reliability criteria, for use in directly establishing safe releases. This approach is valid even if the index flows are only a small fraction of the total local flows. A simple method is as follows:

a. Plot observed hydrographs for the index station and corresponding hydrographs of local runoff at the damage center for as many historical floods as possible. A schematic representation of a local flow area and an index area is shown in fig. 2.01a.

b. Determine a time of flood wave travel, t, from the reservoir to the damage center. Shift the local flow hydrographs a time period t earlier. This is illustrated in fig. 2.01b.

c. Shift the index-flow hydrographs so that peaks are coincident with the peaks of the translated local flow hydrographs. The length of time an index hydrograph is shifted is the "time of advance warning," T, as illustrated in fig. 2.01b. If T is negative, the index flow occurs too late to provide a good warning, but index flow can still be used to some advantage in the same manner. Adopt a "representative" value of T for subsequent steps in the procedure.

d. For each flood, plot simultaneous values at frequent intervals, of the two translated hydrographs from steps "b" and "c". The two translated hydrographs are shown dashed in fig. 2.01b, and plotted points are shown in fig. 2.01c. Draw a line enveloping the highest values of damage-center local flows so that the line is smooth and passes through the origin, as in fig. 2.01c.

e. Construct a "release curve" from this "envelope curve" by plotting the difference between the target flow and the envelope value of local flow against the index flow, as in fig. 2.01d. Fig. 2.01d can
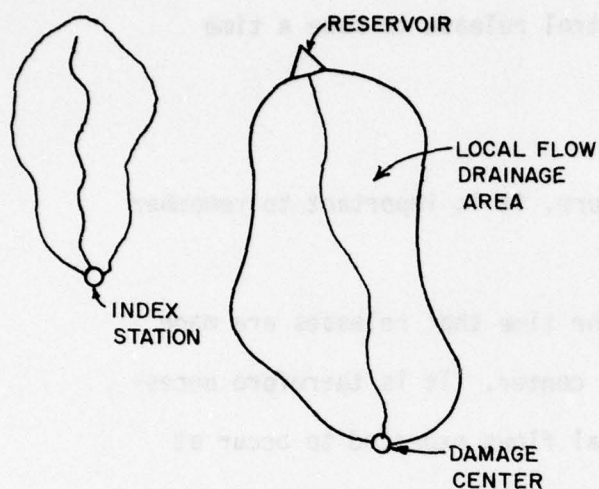
a. SCHEMATIC DIAGRAM
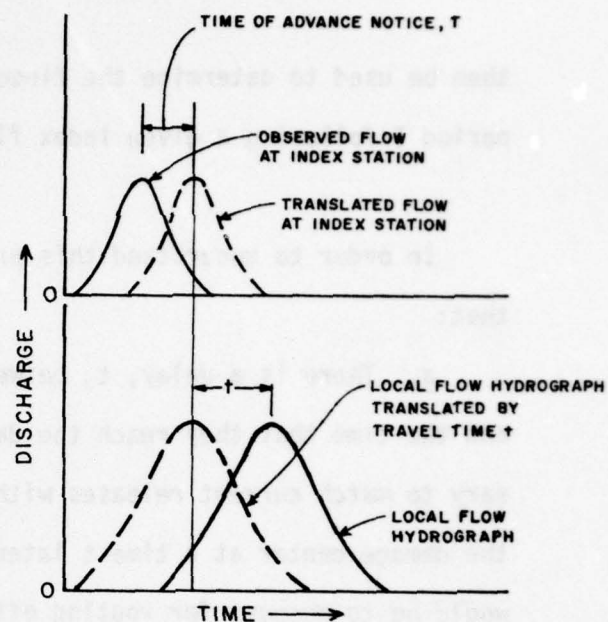
b. ILLUSTRATIVE HYDROGRAPHS
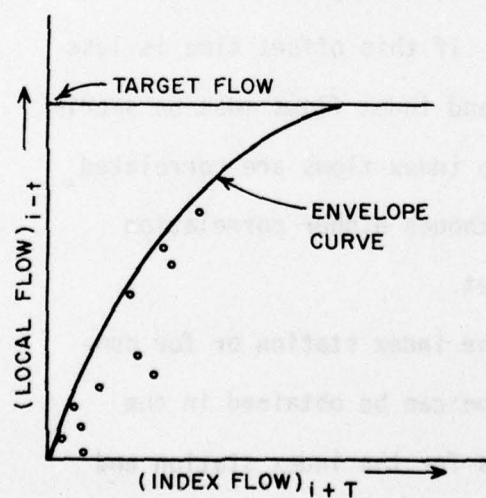
c. ENVELOPE CURVE
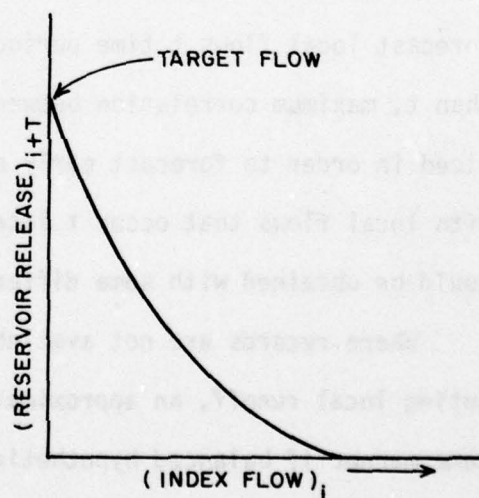
d. RELEASE CURVE

Fig. 2.01. Development of reservoir release rate

then be used to determine the flood control release to make a time period T following a given index flow.

In order to understand this procedure, it is important to remember that:

<u>a</u>. There is a delay, t, between the time that releases are made and the time that they reach the damage center. It is therefore necessary to match current releases with local flows expected to occur at the damage center at a time t later. A refinement to the procedure would be to account for routing effects by obtaining the translated local flows by a reverse routing process rather than pure lagging.

<u>b</u>. Maximum correlation between some index-station flows and local flows is obtained if local flows are offset in time so that the peak local and peak index flows coincide. If this offset time is greater than t, there will be some advance warning time using index flows to forecast local flows t time periods later. If this offset time is less than t, maximum correlation between local and index flows must be sacrificed in order to forecast early enough, so index flows are correlated with local flows that occur t later, even though higher correlation could be obtained with some different offset.

Where records are not available for the index station or for computing local runoff, an approximate relation can be obtained in the same manner if balanced hypothetical floods for the index station and local runoff were computed for several sizes of floods using procedures described in Volume 5. An error allowance for forecasting local flow from index flow should be added to the local flow. The amount would

2-06

depend on the suitability of the index station and the consequences of exceeding target flows at the damage center, and would range typically between 25 and 100 percent of the forecasted local flows.

Where more than one downstream damage center must be protected on a forecast basis by a reservoir, this entire process is repeated for each damage center, and the smallest current allowable release is adopted.

Section 2.03.   Computer-Aided Forecast Procedures

In the index approach just described, reservoir releases are based on runoff that is occurring at an "index" station, and use is not made of precipitation information. Computer-aided forecast procedures currently (1975) available in the United States employ sophisticated precipitation-runoff models that can utilize precipitation forecasts in determining streamflow forecasts. Three computer programs that are used on an operational basis for forecasting streamflows are described in references 1, 4, and 11.

In order to determine reservoir releases for planning studies where flows throughout the basin are known, or for real-time flood operations where forecasted flows are developed by an external procedure, the procedures employed in computer program HEC-5C, Simulation of Flood Control and Conservation Systems, have been found to be useful. Exhibit 2 of Appendix 1 illustrates the procedure.

CHAPTER 3. REGULATION OF RESERVOIR DESIGN FLOOD

In cases where a specific observed or hypothetical reservoir design flood has been adopted as a basis for establishing flood control space, the amount of space required is determined by performing a routing (an operation study) of that flood. Routings can be performed by manual methods or by using a computer program such as HEC-5C. The initial storage in the reservoir used in such a routing should be the maximum storage that could reasonably be anticipated at the start of a major flood. In general, this would be storage at the top of the conservation pool, which includes storage required for all purposes other than flood control (including a reserve for sedimentation). No storage should exist in the flood control space at the start of a reservoir design flood, because this flood should include all periods of heavy runoff that would cause storage in the flood control space and affect the maximum reservoir stage during that flood.

Releases made during the reservoir design flood are controlled by outlet capacity and by target flows downstream of the reservoir. During those periods when the controlling constraint is downstream of the reservoir, the operation study is performed by adding the inflow volume during any computation interval to the storage at the start of that interval and subtracting the average release during that interval that would be permitted by downstream controls. During times when releases are controlled by outlet capacity or are otherwise a unique function of storage, routing is performed by use of storage-indication curves,

3-01

because outflow changes during the computation interval and must be estimated at the start of the interval. The general routing procedure is as follows:

a. Compute the average reservoir inflow, including rainfall on the lake, for each computation interval of the flood.

b. If outflow is strictly a function of storage during any portion of the flood, prepare a storage-indication curve by plotting outflow against storage indication. Storage-indication is equal to half of the outflow plus all of the storage, where storage is expressed in volume units that represent one unit of outflow continuing for one computation interval of time. This is illustrated in table 3.01 and fig. 3.01.

c. Where outflow is strictly a function of storage, start with the storage indication value corresponding to the specified initial storage, subtract the corresponding outflow and add the average inflow for the computation interval to obtain storage indication for the end of the computation interval. A value of outflow for the end of the interval is then read from the storage-indication curve. This step is repeated for each interval, starting with the new storage-indication value, as illustrated in table 3.02. Fig. 3.02 illustrates the routing graphically.

d. Where outflow depends on conditions downstream, determine the average outflow for each current interval in accordance with the regulations, subtract from initial storage for the interval and add average inflow for the interval to obtain storage at the end of the interval. Storage must be expressed in volume units corresponding to one unit of

outflow (and inflow) continuing for one interval. This step is repeated for each interval of the flood.

e. The outflow hydrograph obtained in this manner should be routed to downstream damage locations and combined with local runoff to evaluate effects of design-flood regulation. Generally the outflow determination for downstream conditions requires an iterative process of trial releases and routing to determine the maximum release that can be made without causing flooding. Examples of a hand computation and computer solution for an operation study for a single reservoir operating for two downstream control points is shown in Exhibit 2 of the HEC-5C Users Manual (Appendix 1).

Table 3.01. Computation of storage indication

Elevation	Storage		Outflow	Storage-Indication
(meters)	(million m^3)	(cms-2hr)	(cms)	(cms-2hr)
128	778	108,000	0	108,000
130	864	120,000	2,000	121,000
132	950	132,000	8,000	136,000
134	1,037	144,000	18,000	153,000
136	1,123	156,000	30,000	171,000
138	1,210	168,000	44,000	190,000

If the results of the reservoir operation study for a given design are not satisfactory, either because flows are too high or reservoir storage is not fully utilized, the reservoir size, outlet capacity or operation method should be changed, and a new routing performed. This
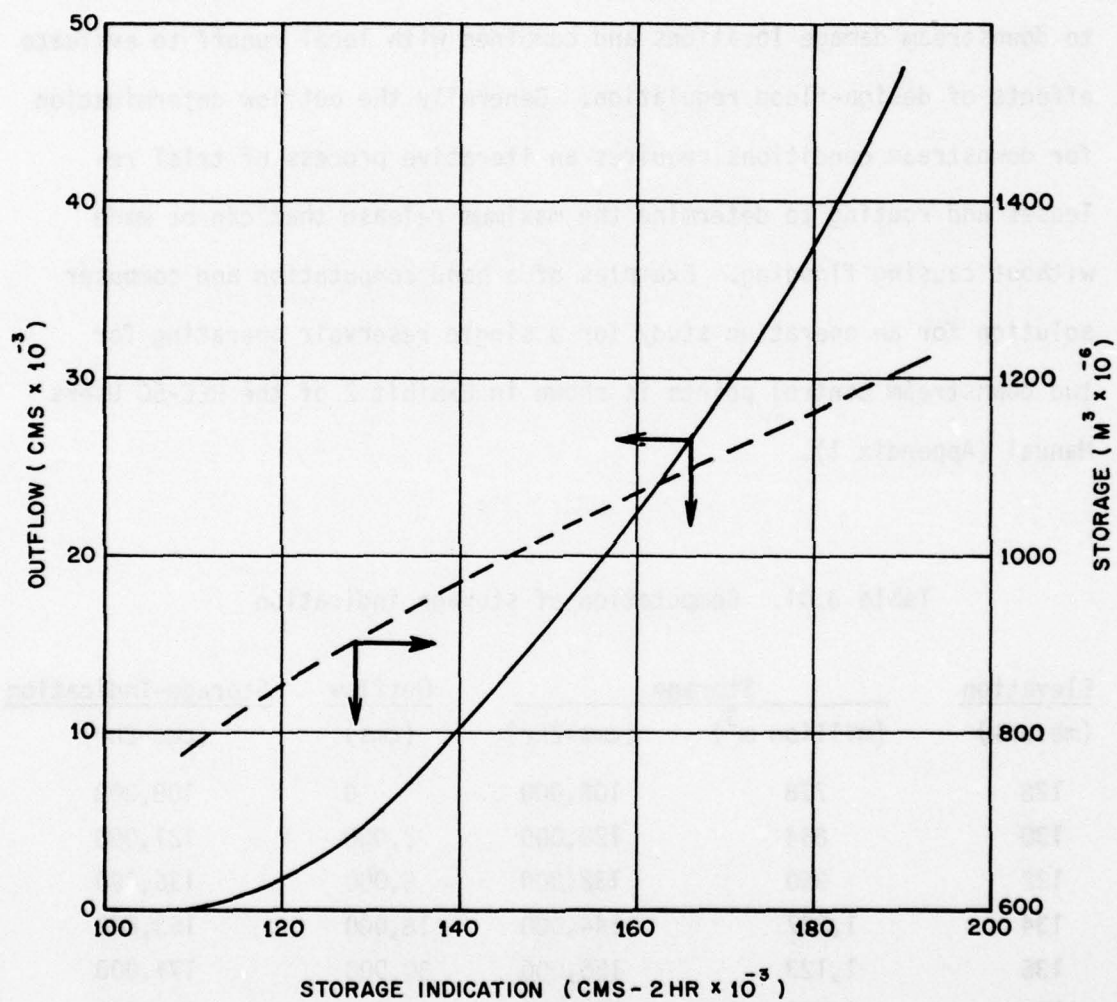
Fig. 3.01. Storage indication curve

Table 3.02.   Reservoir routing

Time	Average Inflow	End-of-Period Storage Indication	End-of-Period Outflow	End-of-Period Storage
(hours)	(cms)	(cms-2 hr)	(cms)	(million m^3)
		108,000	0	778
0-2	20,000	128,000	4,500	906
2-4	30,000	153,500	18,500	1,040
4-6	50,000	185,000	40,000	1,188
6-8	45,000	190,000	44,000	1,210
8-10	30,000	176,000	34,000	1,146
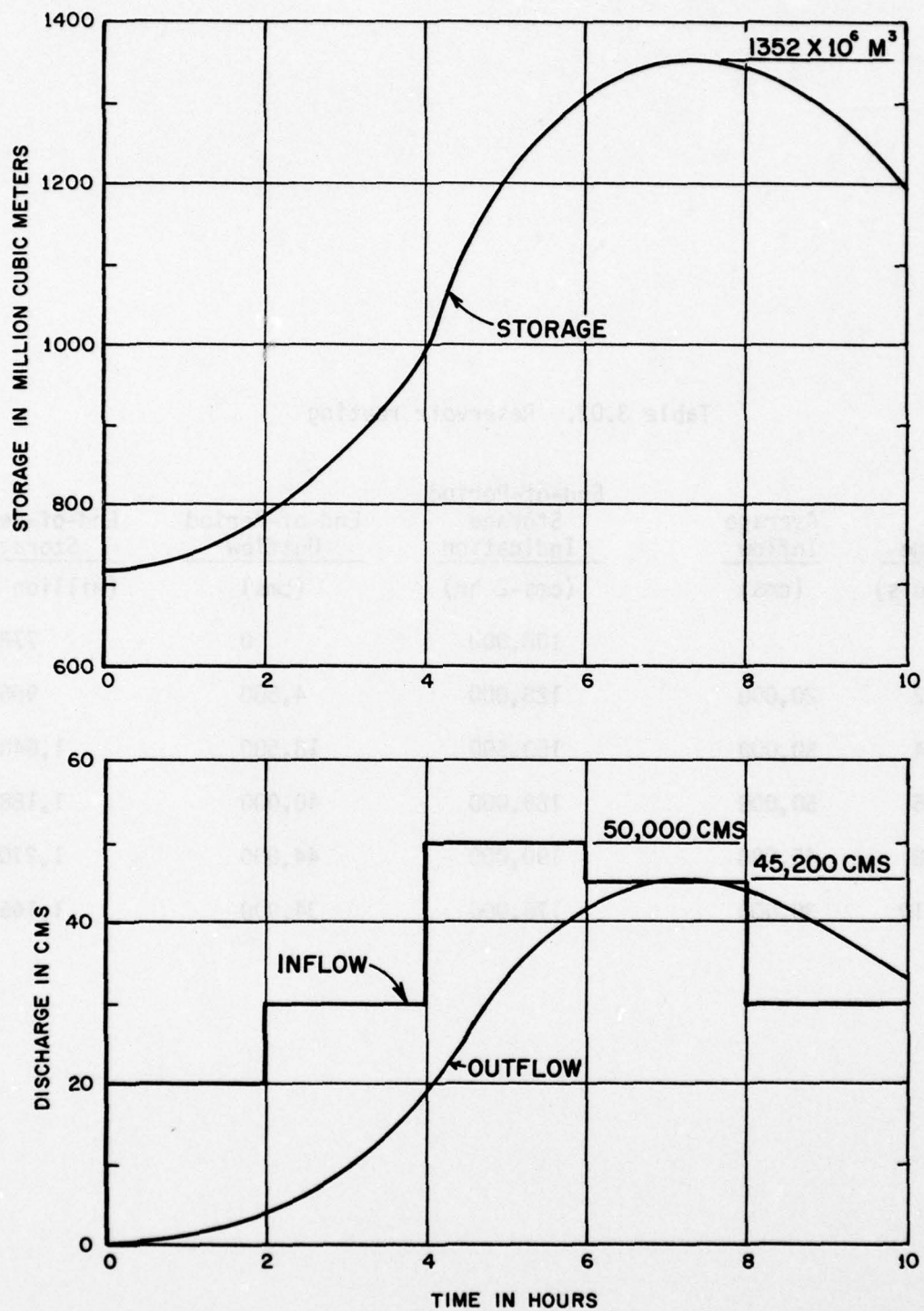
Fig. 3.02. Operational hydrographs of reservoir routing
- uncontrolled spillway

process is repeated until a design is obtained that will provide a satisfactory degree of protection at minimum cost. In this procedure, a graphical representation of pertinent flows such as is illustrated in fig. 3.02 can be helpful in estimating how changes in release schedules would change storage requirements or how changes in storage capacity would change the capability to control releases. Changes in downstream flow volumes must correspond to changes in the volume of water stored or released from the reservoir.

CHAPTER 4. REGULATION OF EXPECTED FLOODS

The degree of flood protection provided by a reservoir may vary seasonally or stochastically with varying hydrologic conditions. For example, when flood control requirements conflict seriously with other project functions, it may be advisable to compromise and reduce the degree of flood protection during certain periods of the year. As another example, an extended period of drought could result in substantial empty space within the conservation pool at the start of a major flood, in which case a higher degree of protection than usual would be provided. In order to evaluate any plan of operation, it is necessary to integrate the effects of all combinations of conditions and potential flood magnitudes that can prevail.

A complete evaluation of a plan of operation could theoretically be made if the operation of the reservoir were studied in detail under conditions prevailing during hundreds of years, presuming that all of the important combinations of initial conditions, downstream conditions and inflow conditions would be adequately represented in such a long period of time. However, it is not ordinarily feasible to perform such extensive computations, and some means must therefore be employed for approximating the results that would be obtained.

The most common method of evaluation is to route all major histori-al floods through the reservoir for one or more conditions of initial storage. One assumed condition might be that the reservoir flood space is empty at the beginning of the flood. Another procedure would be to

base the starting storage on the results of monthly operation studies.

Where reservoir conditions at the start of each flood are not essentially constant as in the case of a reservoir operated for flood control only, it is sometimes satisfactory to select a typical flood pattern for inflows and one for local flows downstream and to route eight or ten sizes of floods (ratios of the typical flood hydrographs) through the reservoir and downstream, using techniques described in the preceding chapter. The frequency of occurrence of each regulated flood is considered to correspond to the frequency of occurrence of the corresponding unregulated flood. This rule is satisfactory as long as the pattern used is reasonably typical of the various flood patterns that occur at the location. Where different types of floods occur, such as snowmelt, general rain floods and cloudburst floods, it would be necessary to perform this operation for each type of flood. Separate frequency curves of unregulated flows would be required for each type of flood.

Where reservoir conditions at the start of each flood can be materially different, the above set or sets of flood routings should be repeated for each of various starting conditions. This would give a frequency curve of regulated flows for each starting condition. These must then be combined into a single frequency curve of regulated flows as follows:

a. Determine from a monthly multipurpose operation study the proportion of time that each starting condition (range of initial storage) will prevail during the flood season.

4-02

<u>b</u>. For each of various specified magnitudes of regulated flows, multiply the frequency indicated for each starting condition by the proportion of time that the starting condition prevails.

<u>c</u>. Add these products to obtain the frequency of the specified flow magnitude.

This procedure for obtaining a frequency curve is illustrated in Section 8.06 of Volume 3.

The computer program HEC-5C described in Appendix 1, can be used to perform monthly multipurpose reservoir routings and short interval flood routings during the same computer run. The program can also be used for performing reservoir system flood operation studies for up to nine ratios of any number of flood patterns, and can compute regulated frequency curves and expected average annual flood damage with and without the reservoir systems.

CHAPTER 5. OUTLET CAPACITIES

Outlets and gates provided at reservoirs should be adequate to perform the services for which the reservoir is to be operated. These should include routine operation requirements, potential changes in operation functions and objectives, and requirements for project servicing and safety. In the last category are emergency gates for closing outlets for repairs to the main service gates, and gates which provide outlet capacity near the bottom of the reservoir to drain the reservoir to the extent necessary for emergency repairs.

The outlet capacity usable for functional operation purposes is that which can reasonably be depended upon when needed. It must be ascertained that gates can be operated safely at partial or full opening, as might be necessary, under all hydraulic heads that can prevail. If the discharge capacity of hydroelectric turbines is to be counted upon for other purposes, it is necessary that they be operable when needed, regardless of variations in power load.

The discharge capacity of outlets is computed in accordance with the general equation:

$$Q = CAH^{1/2}$$

where:

Q = discharge rate

C = coefficient of discharge and unit conversion

A = cross-sectional area

H = vertical distance from static water level to centroid of A or to downstream tailwater, if higher

Values for the coefficient C are obtainable from standard hydraulics handbooks, but model tests for evaluating C should be made where unusual conditions exist and discharge determinations are critical, particularly for partial gate openings. Reference 8 provides information on calculation of rating curves for outlet works. Where possible, outlet discharge rating curves should be checked by prototype measurements downstream as soon after project construction as is feasible.

Where very large release capacities are required for flood control it might not be economically feasible to follow the normal procedure of providing outlet capacity for full flood-control releases when the reservoir stage is at the top of the conservation pool. If full release capacity is not provided, it should be remembered that reduced outlet capacity must be accompanied by increased storage capacity, or else the flood control effectiveness will be reduced. The proper balance among outlet capacity, storage capacity, and degree of flood protection provided can be obtained through studies of costs and benefits and consideration of other factors such as safety and minimum protection standards. Such studies would include comprehensive flood routings as discussed in Chapter 4.

There are occasions where local inflows above downstream damage locations are so large as to severely restrict the releases that can safely be made from the reservoir during critical flood periods. In such cases, outlet capacity substantially below downstream channel capacities might be adequate. In order to select the best release capacity, comprehensive flood routings discussed above should include typical sequences of floods long enough to assure that expected sequences of floods can be adequately regulated.

In the case of a flood control reservoir emptying into a downstream flood control reservoir, the outlet capacity of the upstream reservoir should be sufficient to assure that its flood control space can be emptied during the period when high tailwater exists due to water being stored in the flood control space at the downstream reservoir, under any reasonable distribution of inflows to the two reservoirs. This will assure that the reservoir system can operate efficiently by making full required releases from the downstream reservoir whenever water is stored in flood control space at either reservoir.

In the case of two flood control reservoirs on separate tributaries above the same damage center, the outlet capacity of each should be large enough to supply target flows at the damage center with minimum expected simultaneous release from the other reservoir. Again, this provision is necessary to assure the capability of making full flood control target flows at the damage location whenever water is in flood control space at either reservoir. This is subject to provisions discussed above for cases where local runoff below the reservoirs and above the damage center is so large as to warrant smaller outlet capacities.

CHAPTER 6. SPILLWAY OPERATION

Section 6.01. Considerations for Spillway Operation

The primary purpose of a spillway is to prevent overtopping of the dam by flood flows in excess of those which the project is designed to regulate, up to the spillway design flood. There are other purposes for which a spillway may be used, however. For example, gates may be added to an existing spillway to permit storage of water above the spillway crest level during periods when it is safe to do so. It is sometimes desirable to close gates on the outlet works to take advantage of the limited capacity of the spillway under low heads and thus prevent downstream damage. This is only feasible, of course, if the flood does not greatly exceed project design magnitudes. Whenever the spillway is used for such secondary purposes, however, every care must be exercised to assure that the gates can and would be operated so as to make the full capacity of the spillway and outlets available when needed for protection of the structure.

The size and characteristics of a spillway are based on economic and operation studies of a spillway design flood. In the case of projects where exceeding the spillway capacity would result in a major disaster, it is important to provide a large enough spillway to pass the probable maximum flood (described in Volume 5) without major structural failure. In other cases, a smaller spillway design flood might be satisfactory. The final design of the spillway should be such that it will

safely pass the spillway design flood occurring at a time when the reservoir is as full as could occur in advance of such a flood, adhering to the specific rules by which the project would be operated under such conditions. The spillway operation must not be dependent on communications that are subject to failure or on expert analysis that might not be available at the time.

During floods that make use of the spillway and result in downstream flows that are damaging, the following precautions are necessary:

<u>a</u>. Outlet and spillway gates should not be opened so rapidly that damaging flows downstream will be larger than would occur without the project.

<u>b</u>. Opening of gates must start early enough to allow an orderly opening of the gates to their full capacity without storing water above the maximum safe level in the reservoir.

<u>c</u>. Damaging flows should not be released before it is certain that the flood cannot be completely controlled, but should be released at a specified rate as an emergency measure as early as is feasible after it is certain the flows of that magnitude or larger are inevitable and would have occurred by that time without the project.

Induced surcharge operation may be used to exercise partial control over outflow rates after the reservoir has filled to the static-full-pool level. Induced surcharge storage is storage above the static-full-pool. Regulation is accomplished by raising all gates by small increments, forcing into surcharge storage all inflow in excess of the discharge capacity of the spillway with the gates at selected openings. The elevation attained and volume of induced surcharge used will vary

6-02

with the volume and rate of reservoir inflow in individual floods and the exact schedule of gate operations in each case. The maximum elevation of induced surcharge that is practicable to provide for in the design of projects involving gated spillways usually is limited to approximately 1 to 3 meters.

Section 6.02. Development of Emergency Release Schedules

In order to assure that the project operation will be able to comply with necessary precautions under extreme flood conditions, it is advisable to provide an emergency release diagram that uses only information on reservoir data immediately available to the operator. Such an operation diagram is illustrated in fig. 6.04 and is developed as follows:

a. Develop a set of spillway-rating curves which shows the discharge that would occur as all spillway gates are raised collectively by successive increments of about 1 foot (.3 meter) until fully opened. A set of curves is shown in fig. 6.01.

b. Construct an "induced surcharge envelope curve" from a point corresponding to the nondamaging flood control release at the static-full-pool elevation to the free discharge capacity of the spillway corresponding to the elevation at which all gates must be fully opened. This is illustrated by curve E, fig. 6.01. A straight-line connection would assure the minimum rate of increase in spillway discharge under critical flood conditions, and may be the proper selection in some cases. However, curvature as illustrated in fig. 6.01 permits a lower release

Fig. 6.01

TRUNNION

Top of gate corresponding to various openings

RADIUS = 32.5'

Bottom of gate corresponding to various openings

GATE SEAT EL. 671.0

TAINTER GATE DIAGRAM

GATE OPENINGS IN FEET

TOP OF FLOOD CONTROL POOL EL. 701.0

RATING WITH ALL GATES FULLY OPEN

SPILLWAY CREST

DISCHARGE IN 1000 C.F.S.

SPILLWAY RATING CURVES

RESERVOIR WATER SURFACE ELEVATION IN FEET, M.S.L.

NOTES: Spillway equipped with seven 40ft. x 29ft. tainter gates.
All gates are assumed to open uniformly.
Gate openings represent vertical distance of lower edge above gate seat.
Curves of partial gate openings were estimated from model tests of similar structures.
Curve G corresponds to top of the gates at various openings.
Curve E represents a limiting relation of gate opening and reservoir level.
When reservoir level corresponding to a given gate setting is below the E curve, outflow is regulated by the size of gate opening not to exceed natural flow conditions at the dam site.

GATED SPILLWAY DISCHARGE CHARACTERISTICS

rate in the lower surcharge ranges which would be the most frequently utilized. The minimum permissible slope of the line at the higher elevations is governed by the rate of increase in spillway discharge that may be considered acceptable during infrequent and extraordinary floods.

c. Analyze recession characteristics of inflow hydrographs to obtain a recession constant that will be used in predicting a minimum inflow volume that can be expected when only reservoir elevation and the rate of rise of reservoir elevation are known. For conservative results the assumed recession curve should be somewhat steeper than the average observed recession and normally can be patterned after the spillway-design flood recession. The recession constant can be obtained by plotting the recession curve as a straight line on semilog paper, with the flow on a logarithmic scale and time on an arithmetic scale. The recession constant, T, is defined as the time required for the discharge to decrease from any value, say Q_A, to a value Q_B, where Q_B equals $Q_A/2.7$.

d. A relationship to compute the volume of water that must be stored for a hydrograph receded from an initial flow to a constant outflow can be derived from continuity considerations. Consider fig. 6.02,
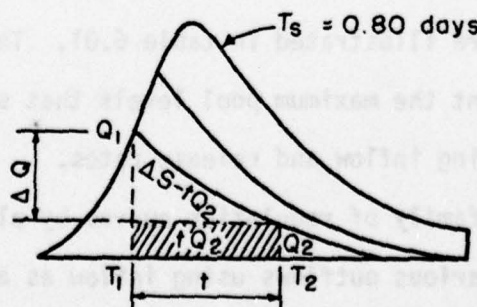
Fig. 6.02. Schematic hydrograph

which schematically illustrates terms to be used in solving for the volumes to be stored, S_A. In the fig. 6.02, Q_1 represents the inflow and Q_2 represents the constant outflow. The recession constant, T_s, may be defined as

$$T_s = \frac{\Delta S}{\Delta Q} = \frac{\frac{S_A}{2} + Q_2 t}{Q_1 - Q_2} = \frac{S_A + 2Q_2 t}{2(Q_1 - Q_2)} \tag{6-1}$$

then,

$$t = T_2 - T_1 = -T_s \log_e \frac{Q_2}{Q_1} = T_s \log_e \frac{Q_1}{Q_2} \tag{6-2}$$

Substituting (6-2) into (6-1) and rearranging

$$S_A = 2T_s (Q_1 - Q_2 - Q_2 \log_e \frac{Q_1}{Q_2})$$

$$= 2T_s [Q_1 - Q_2 (1 + \log_e \frac{Q_1}{Q_2})] \tag{6-3}$$

For each of various inflow rates and for each of various outflow rates, compute the volume of water that must be stored, S_A, using equation 6-3. Then determine pool levels by subtracting S_A from the storage value for the given outflow as defined by the "induced surcharge envelope curve." The computations are illustrated in table 6.01. The pool levels thus determined represent the maximum pool levels that should be permitted for the corresponding inflow and release rates.

_e_. Obtain a family of regulation curves by plotting the pool levels corresponding to various outflows using inflow as a parameter. The family of curves is shown in fig. 6.03.

6-06

TABLE 6.01

Computations for Spillway Gate Regulation Schedule							

Spillway gates: 40 x 26 ft
Spillway crest elev: 835
$T_e=0.67$

Equation: $S_A=2T_e[Q_1-Q_2(1+\log_e Q_1/Q_2)]$, where at a given instant $Q_1=$ Inflow (c.f.s.), $Q_2=$ Outflow (c.f.s.), $S_A=$ Available storage (acre-ft.) $=$ Limiting Surcharge storage $(S_e)-$ Actual storage (S_I), and $T_e=$ Adopted inflow recession constant (days)

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
Q_1 (1,000 c.f.s.)	Q_1/Q_2	$1+\log_e Q_1/Q_2$	$Q_2\times$col. 3 (1,000 c.f.s.)	$K=$ col. 1 $-$ col. 4 (1,000 c.f.s.)	$S_A=$ $2T_e\times$col. 5 (1,000 acre-ft.)	$S_I=$ S_e-col. 6 (1,000 acre-ft.)	Pool elevation
	$Q_2=0$				$S_e=660.5$		
				0	0.0	660.5	859.5
10			0.0	10	13.4	647.1	858.8
20				20	26.8	633.7	858.1
30				30	40.2	620.3	857.3
40				40	53.6	606.9	856.6
	$Q_2=10$				$S_e=675.9$		
10	1.00	1.000	10.0	0.0	0.0	675.9	860.3
20	2.00	1.693	16.9	3.1	4.2	671.7	860.1
30	3.00	2.099	21.0	9.0	12.1	663.8	859.7
40	4.00	2.386	23.9	16.1	21.6	654.3	859.2
50	5.00	2.609	26.1	23.9	32.0	643.9	858.6
	$Q_2=20$				$S_e=687.8$		
20	1.00	1.000	20.0	0.0	0.0	687.8	860.9
30	1.50	1.405	28.1	1.9	2.5	685.3	860.8
40	2.00	1.693	33.9	6.1	8.2	679.6	860.5
50	2.50	1.916	38.3	11.7	15.7	672.1	860.1
60	3.00	2.099	42.0	18.0	24.1	663.7	859.7
70	3.50	2.253	45.1	24.9	33.4	654.4	859.2
	$Q_2=30$				$S_e=700.3$		
30	1.00	1.000	30.0	0.0	0.0	700.3	861.5
40	1.33	1.285	38.6	1.4	1.9	698.4	861.4
50	1.67	1.513	45.4	4.7	6.3	694.0	861.2
60	2.00	1.693	50.8	9.2	12.3	688.0	860.9
70	2.33	1.846	55.4	14.6	19.6	680.7	860.5
80	2.67	1.982	59.5	20.6	27.6	672.7	860.1
90	3.00	2.099	63.0	27.0	36.2	664.1	859.7
	$Q_2=40$				$S_e=715.4$		
40	1.00	1.000	40.0	0.0	0.0	715.4	862.2
50	1.25	1.223	48.9	1.1	1.5	715.9	862.1
60	1.50	1.405	56.2	3.8	5.1	710.3	862.0
70	1.75	1.560	62.4	7.6	10.2	705.2	861.7
80	2.00	1.693	67.7	12.3	16.5	698.9	861.4
100	2.50	1.916	76.6	23.3	31.2	684.2	860.7
120	3.00	2.099	84.0	36.1	48.4	667.0	859.8
140	3.50	2.253	90.1	49.9	66.9	648.5	858.9
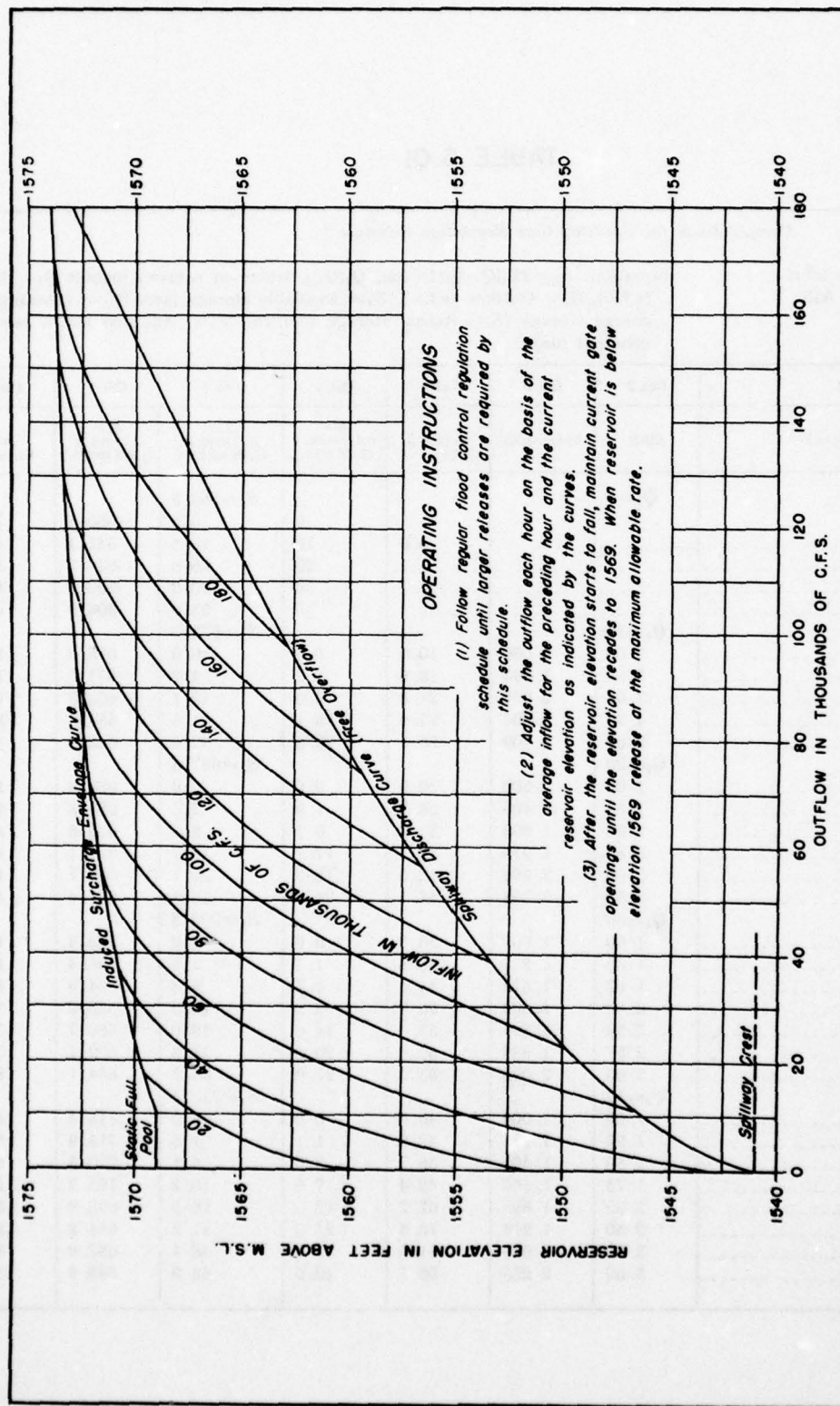
Fig. 6.03. Spillway gate regulation curves based on inflow

<u>f</u>. A family of curves such as those shown in fig. 6.03 are appro-
priate for use in a central office, but relationships to be used as an
emergency operation schedule for damtenders are more directly usable
if the rate of rise of reservoir level is substituted for the inflow.
This is readily accomplished by obtaining the difference between the
volume of inflow and outflow for a selected time interval and expressing
the volume as a rate of rise for any particular reservoir elevation. A
typical family of curves is shown in fig. 6.04. The time interval to
be used as a basis for determining rate of rise should be based on a
consideration of the reservoir and drainage basin characteristics, with
1 to 3 hours being typical. Adjustment in gate openings at 1- or 2-hour
intervals is adequate for most projects.

A computer program Spillway Gate Regulation Curve, described in
Appendix 5, has been developed for computing gate regulation schedule
curves for a reservoir utilizing area-capacity curves, an induced sur-
charge envelope curve, and a constant recession constant, T_s.

Section 6.03. Initial Reservoir Level

The spillway discharge capacity and peak reservoir level likely to
be attained during the spillway design flood will be governed by,

<u>a</u>. The spillway design flood inflow hydrograph.

<u>b</u>. The reservoir level at the beginning of the spillway design
flood inflow.

<u>c</u>. The plan of reservoir regulation.
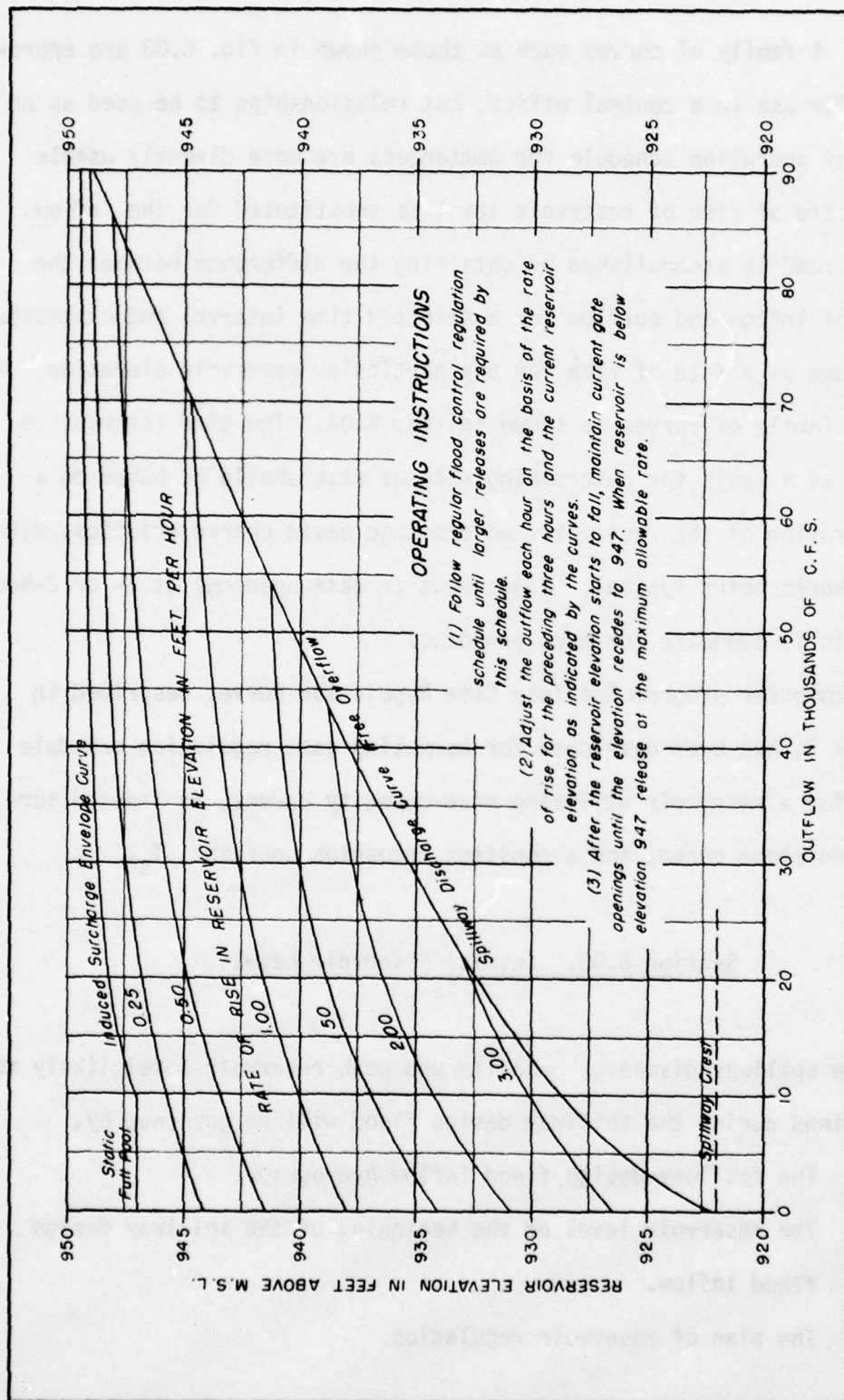
Fig. 6.04. Spillway gate regulation curves based on rate of rise

If the flood control space in the reservoir below the "normal full pool elevation" (top of flood control pool) is relatively large in proportion to the spillway design flood volume, the initial pool level assumed in flood routing studies can have a major influence on estimates of spillway discharge requirements and surcharge heights. Some considerations in selecting initial stages are quoted below from Corps of Engineers manuals.

As a general rule there is no reliable rational way of estimating the initial reservoir level that is likely to prevail at the beginning of the spillway design flood, except when the storage space is so small as to assure frequent filling. If a long period of streamflow records is available, hypothetical reservoir regulation studies will provide some index to reservoir elevation probabilities, but even these computed relations may be greatly altered in the future if changing conditions result in substantial alterations in the reservoir regulation plan (as is often the case). In addition, reallocations of flood control space to some other use in the future may result in higher pool levels at the beginning of the spillway design flood. In any case, an unusual sequence of floods can result in filling all or a major portion of the flood control space in a reservoir immediately before the beginning of the spillway design flood.

In view of the uncertainties involved in estimating initial reservoir levels that might reasonably be expected to prevail at the beginning of the spillway design flood, it has been common practice in studies prepared by the Corps of Engineers to assume the reservoir is initially filled to the "normal full pool level" if routing of representative major

floods of record, or the hypothetical Standard Project Flood (occurring

5 days in advance of the spillway design flood), shows that such a

level (or higher) might prevail at the time the spillway design flood

occurs. If the spillway design flood estimate is associated with a

particular season, the determination of initial pool level would consider

flood conditions on comparable dates.

In many instances the assumption of initial reservoir levels

corresponding to arbitrarily selected percentages of the flood control

capacity will serve to demonstrate the effects that alternative assump-

tions would have on maximum reservoir surcharge levels, and may eliminate

the need for more detailed studies of probable initial pool levels when

the effects are relatively small or moderate. In this connection, it is

usually desirable to assume, for one routing of the spillway design flood

that the design flood control capacity is 50 percent filled at the begin-

ning of inflow. There are several reasons for concluding that the flood

control design storage capacity of a reservoir is likely to be at least

50 percent filled at the beginning of the spillway design flood, regard-

less of the size of the capacity involved. Normally there will be a

relatively large number of floods capable of filling at least one-half

the design flood control space, and most reservoir regulation plans call

for optimum control of these moderate floods. In some cases, reservoir

capacities originally assigned to flood control are reassigned in part

to conservation or similar uses, further increasing the likelihood that

at least 50 percent of the original design capacity will be filled at

the beginning of the spillway design flood. It is also probable that

hydrologic and meteorological conditions required for development of

the maximum probable floods will be preceded by small or moderate flood runoff that would partially deplete available flood control capacities.

A comparison of surcharge elevations computed under alternative assumptions discussed in the previous paragraph usually will reveal whether or not more detailed analysis should be made to establish the most logical starting pool level to be assumed in routing the spillway design flood. If the design flood control capacity is relatively small, there will be little difference between estimated maximum surcharge levels; on the other hand, if the flood control capacity is unusually large in comparison with normal flood runoff quantities, the assumption that the reservoir will be only half filled at the beginning of the spillway design flood would be reasonable in most circumstances. The apparent likelihood that either of these initial pool levels (full or half full) would prevail at the beginning of the spillway design flood can be taken into consideration when the final decisions are reached regarding freeboard requirements for the dam, based on comparison of the effects of alternative assumptions, and other pertinent information.

Section 6.04. Routing the Spillway Design Flood

In establishing the capacity for a spillway of a major dam, a spillway design flood routing should be made and operation rules for such a routing must be adhered to strictly.

A computer program has been developed which will compute a spillway rating curve for an assumed design head and then make a flood routing of the spillway design flood to determine the maximum water surface. A

concrete ogee spillway with vertical walls or a broad-crested weir can be accomodated. The routing can be for a gated or an uncontrolled spillway, and discharge from a conduit or sluice can be included. The program, Spillway Rating and Flood Routing, is described in Appendix 4.

Routing a spillway design flood through a reservoir controlled by a gated spillway is achieved by determining the change in storage during each time period as the difference between inflow and outflow volumes, and adding this change of storage to the total stoarge at the end of the preceding time period. Outflow for a period is determined with a relationship such as that shown in fig. 6.03, using the reservoir elevation at the end of the previous period and the average inflow for the previous period. When a free spillway discharge is reached, the Modified Puls method can be used to continue the routing.

CHAPTER 7. SEASONAL OPERATION VARIATIONS

Section 7.01. General

At almost all locations, floods of any specific type are seasonal
in nature and it may not be necessary to provide all of the flood control
space for that type of flood during part of the year. In formulating
regulations, the seasonal variation in potential of each type of flood
that is important to the design should be examined, and criteria should
be adopted for the use of flood control space for other purposes when
appropriate and desirable.

Section 7.02. Seasonal Rain-Storm Variations

Since rain floods usually occur within a few hours or few days of
the rain storms that cause them, the seasonal distribution of rain floods
can be ascertained by a study of the seasonal distribution of rain storms,
with due consideration given to seasonal variations in ground conditions.
As an example, the results of a study of rainfall frequencies and maxi-
mum recorded rainfall amounts are summarized in fig. 7.01, and data on
outstanding early-season and late-season storms are summarized in
table 7.01 for central and northern California, USA. It is apparent
that storms in this region are most frequent in the months of December,
January, and February, but major storms and floods have occurred in
November and March, and moderate to large storms and floods have occurred

7-01

Fig. 7.01.   Observed and adopted seasonal distribution
of maximum 3-day precipitation

Table 7.01. Maximum observed 3-day precipitation early-season and late-season storms in California

Station	Lat.	Long.	10-yr precip. (in.)	100-yr precip. (in.)	3-day precipitation (in.)	% of 100-yr
					Storm of 26 May 1906	
Magalia	39-48	121-35	15.5	22.8	8.77	38
Emigrant Gap	39-18	120-40	12.8	18.6	6.70	36
Summerdale	37-29	119-39	13.0	19.8	7.42	37
					Storm of 11 May 1915	
Kennett	40-44	122-24	16.4	26.3	13.81	52
Magalia	39-48	121-35	15.8	23.2	12.53	54
Emigrant Gap	39-18	120-40	12.8	18.6	9.90	53
Kentfield	37-57	122-33	8.0	11.4	6.62	58
					Storm of 13 Sept. 1918	
Red Bluff	40-10	122-14	4.6	6.51	7.12	109
Blue Canyon	39-17	120-42	14.5	15.0	5.55	37
Antioch	38-00	121-47	3.3	4.88	6.59	135
San Jose	37-21	121-54	4.0	6.16	6.22	101
					Storm of 6 April 1926	
Dry Canyon Res	34-28	118-32	6.4	11.9	8.5	71
Colbys	34-18	118-07	15.6	30.8	18.3	59
Hoegee's Camp	34-13	118-02	20.9	40.6	25.6	63
Raywood Flats	34-03	116-49	13.8	23.4	14.1	60
					Storm of 25 Sept. 1939	
Squirrel Inn #2	34-14	117-14	15.5	26.6	9.02	34
Mt. Wilson	34-13	118-04	16.0	30.6	11.60	38
Los Angeles	34-03	118-15	6.3	11.2	5.62	50
Fullerton	33-51	117-55	6.0	10.6	5.97	56
					Storm of 30 Oct. 1945	
McCloud	41-15	122-08	9.3	13.6	9.20	68
Shasta Dam	40-43	122-25	14.8	23.7	10.30	43
Upper Mattole	40-15	124-12	12.6	17.2	10.29	60
L. Spaulding	39-19	120-39	12.2	17.7	8.96	51
					Storm of 27 Oct. 1950	
Elk Valley	42-00	123-43	13.5	19.6	15.95	81
Gasquet R. S.	41-52	123-58	13.4	19.0	22.09	116
Orick	41-20	124-02	9.9	14.8	17.79	120
Lakeshore	40-53	122-23	15.8	23.2	14.02	60

Table 7.01. Maximum observed 3-day precipitation
early-season and late-season storms in California (cont.)

Station	Lat. Long.		10-yr precip. (in.)	100-yr precip. (in.)	3-day precipitation	
					(in.)	% of 100-yr
					Storm of 19 May 1957	
Brush Cr. R. S.	39-41	121-22	15.0	23.9	8.15	34
Bullards Bar P.H.	39-25	121-09	10.9	16.3	7.81	48
Gold Run	39-10	120-52	9.4	14.2	7.32	52
Giant Forest	36-34	118-46	12.8	20.1	7.45	37
					Storm of 2 April 1958	
Lehman Ranch	38-36	121-01	5.3	7.58	5.65	75
Drytown	38-26	120-52	5.5	8.19	6.20	76
Hogan Dam	38-08	120-48	6.0	8.59	5.65	66
Oakdale	37-52	120-52	3.5	5.01	7.25	145

7-04

as early as September and as late as May. Weather maps indicate that these last events can be associated generally with the same type of extra-tropical cyclonic disturbances that cause the general winter storms, except that the September 1939 storm is known to be of tropical origin. Important rain floods are unknown in the months of June, July, and August in this region, except for small-area floods resulting from cloudbursts. These, of course, must also be considered in design and operation, but are usually important only in very small basins. Seasonal-variation criteria for central and northern California, based on the information contained in fig. 7.01 and table 7.01, are summarized in fig. 7.02. These criteria are useful as a general guide, but are subject to modification where special conditions warrant. Application methods are described in the next section.

Section 7.03. Seasonal Rain-Flood Variations

The seasonal variation of rain floods can be computed, by hydrograph analysis, from the seasonal variation of rain storms. If a particular flood has been used as a primary basis of project design, loss-rate curves used in deriving that project design flood from the project design storm can be applied to various percentages of the project design storm to delineate the seasonal variation of flood potential. If an official project design flood does not exist, a hypothetical flood could be developed for this specific purpose. Loss rates used in the early part of the rain-flood season should ordinarily be higher than those used in the middle and late parts of the season. Each alternative

7-05
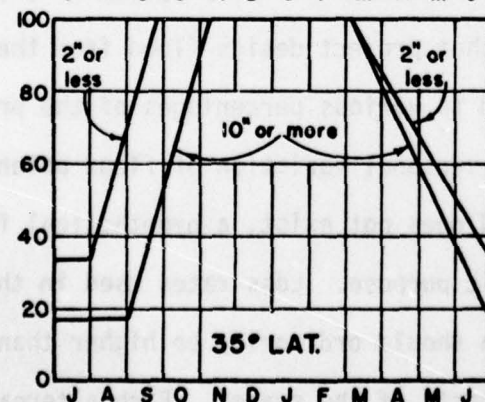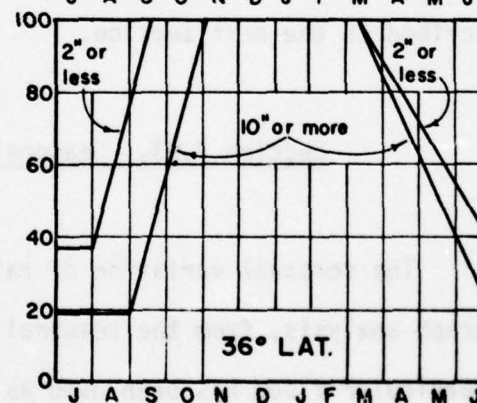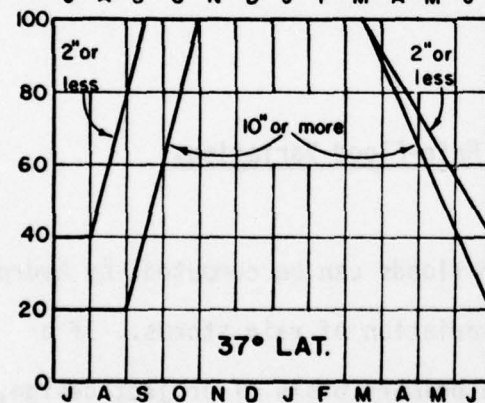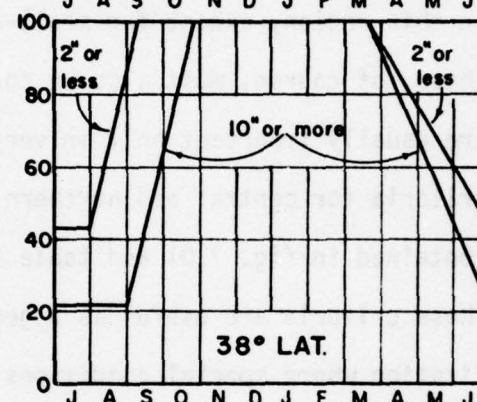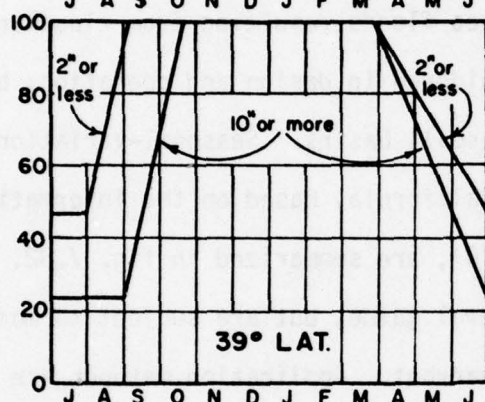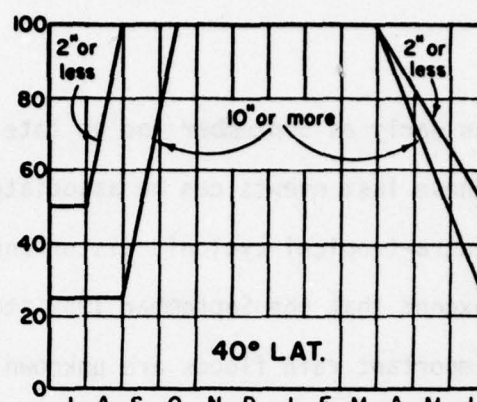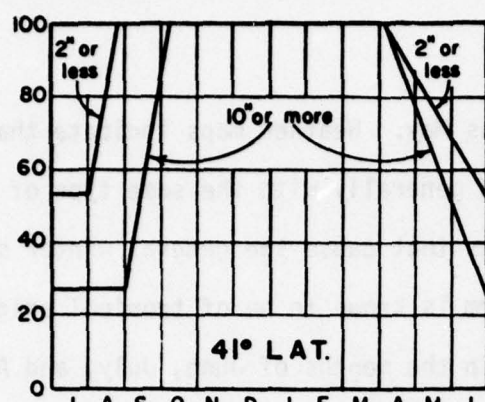
Note:
Parameter is 3-day precipitation exceeded once in 10 years.

Fig. 7.02. Seasonal precipitation distribution criteria

flood would be routed through the reservoir under contemplated operation conditions to determine the amount of reservoir space required. Typical routings are illustrated in fig. 7.03.

The reservoir space requirements thus obtained should be provided on the various dates shown by fig. 7.02 to correspond to the percentage of the design storm used. In this example, based on a latitude of 40° and a 10-year basin-mean storm precipitation of 10 inches in 3 days, fig. 7.02 indicates that the basin can experience full storm potential as early as 15 October and as late as 1 April. Fig. 7.02 also indicates that as much as 80 percent of the full storm potential can be experienced as early as 2 October and as late as 27 April, and as much as 60 percent as early as 18 September and as late as 23 May. Space requirements determined in fig. 7.03 are plotted against these corresponding dates in fig. 7.04 in order to determine maximum space requirements shown in fig. 7.05.

In cases where flood control space is reduced because of dry ground, as discussed in Chapter 6, the required flood-control space for dry ground conditions on these various dates can be established in the same manner, as illustrated in fig. 7.03, except that different loss-rate curves are used, as described in Chapter 8.

Section 7.04. Snowmelt-Season Limitations

Where snow accumulates during the winter and melts mostly during the spring, the use of reservoir space for the control of snowmelt floods can almost always be based on forecasts of runoff volume expected by the end of the snowmelt season. The operation is designed to control the
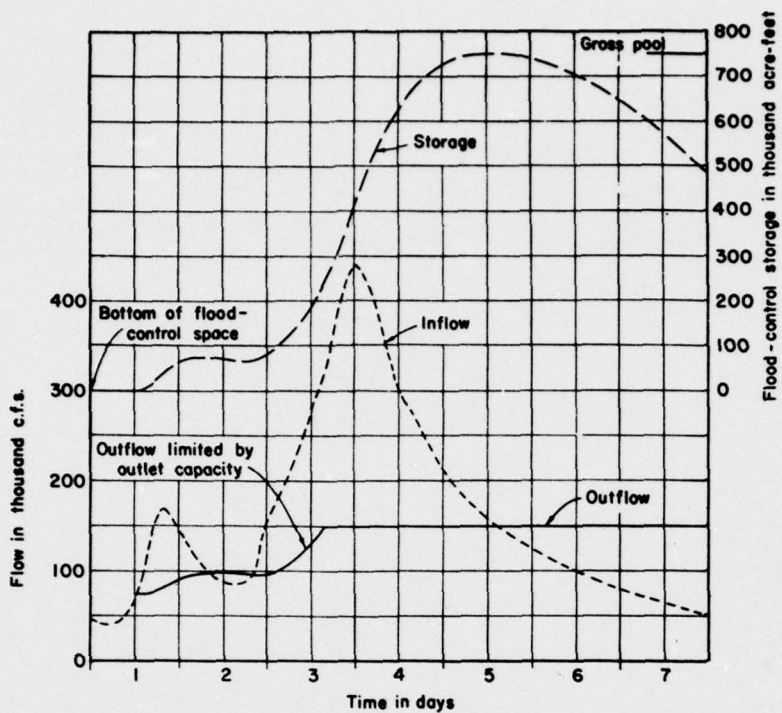
STANDARD PROJECT FLOOD
(STANDARD PROJECT STORM ON WET GROUND)
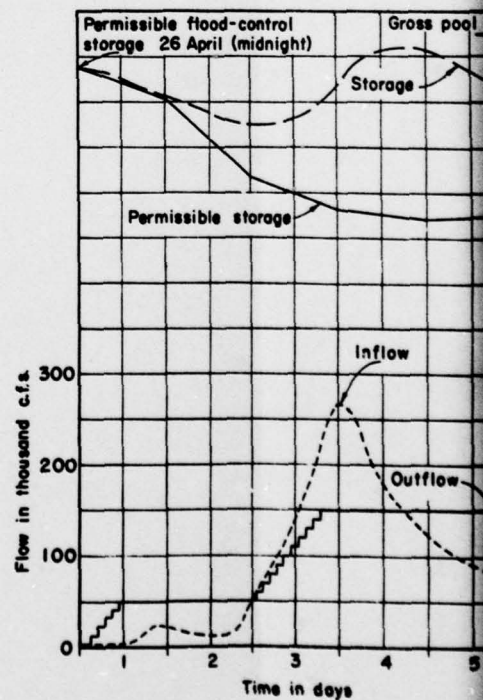
80 PERCENT OF STANDARD PROJ

STANDARD PROJECT STORM ON DRY GROUND

80 PERCENT OF STANDARD PROJECT STORM ON
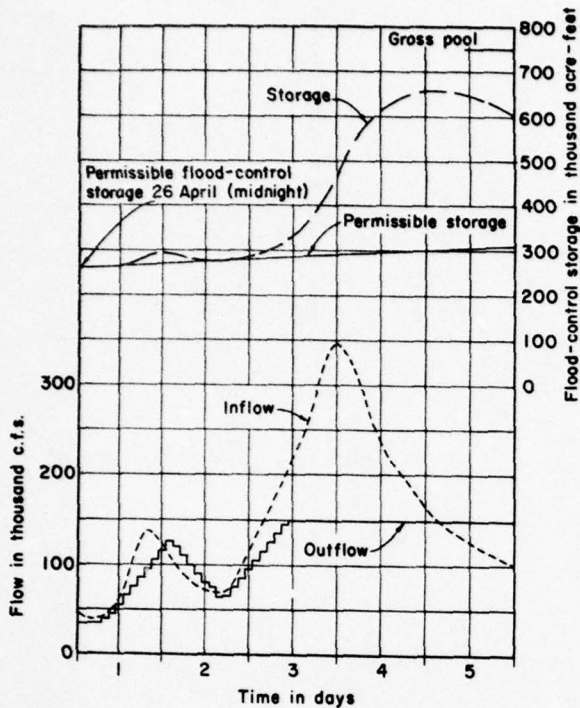
80 PERCENT OF STANDARD PROJECT STORM ON WET GROUND
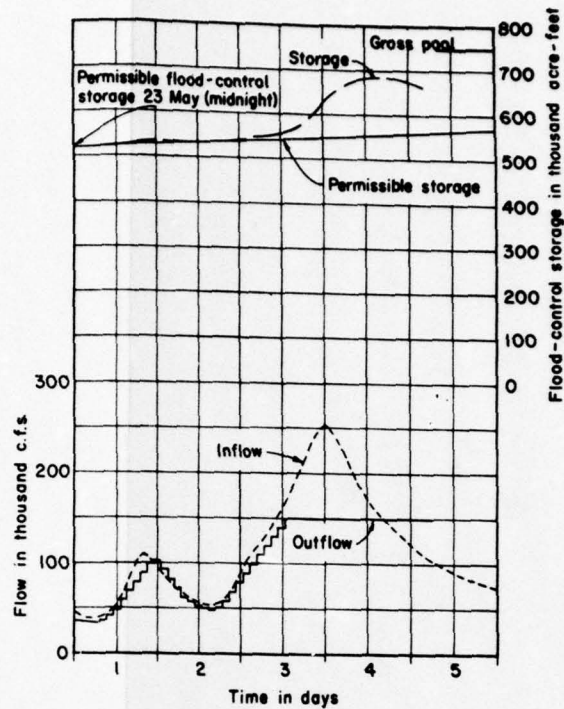
60 PERCENT OF STANDARD PROJECT STORM ON WET GROUND
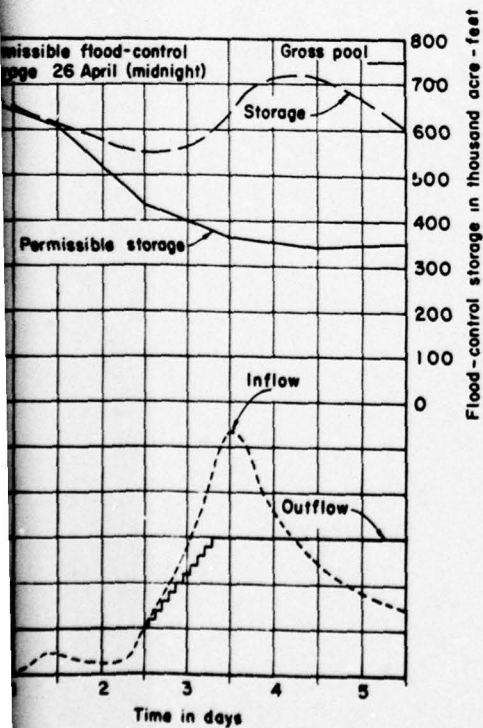
STANDARD PROJECT STORM ON DRY GROUND
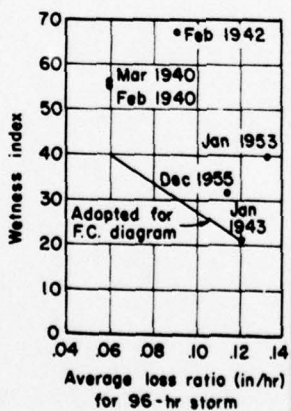
NOTE:
Dry ground conditions are defined as those observed during 1943 storm. Inset at left shows comparison of loss rates observed during major floods studied.

Fig. 7.03. Hypothetical flood routings
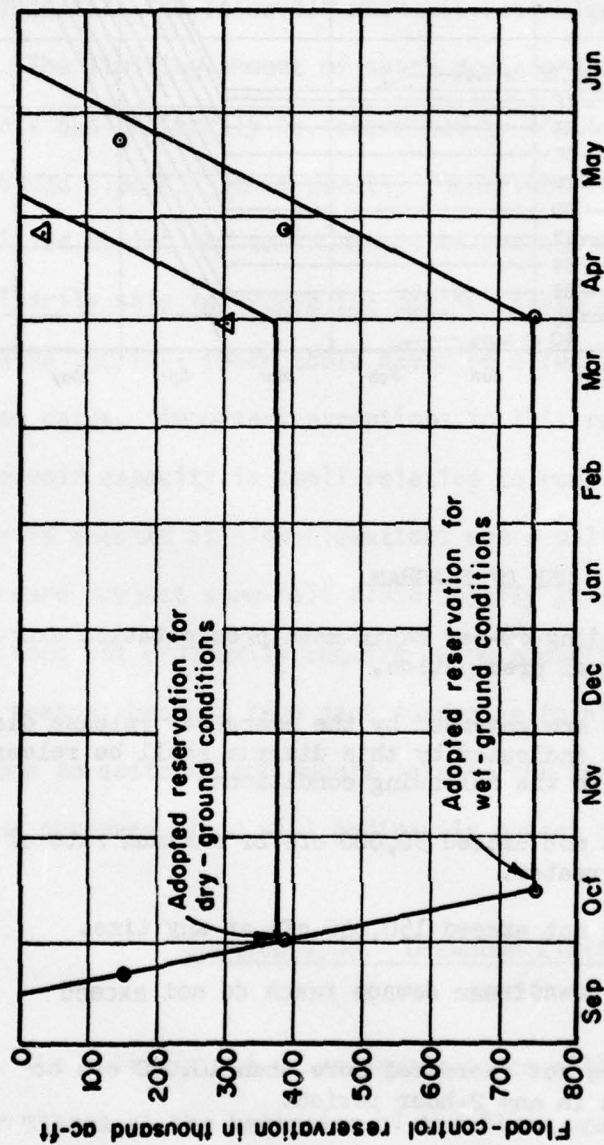
Fig. 7.04. Seasonal flood control space requirement
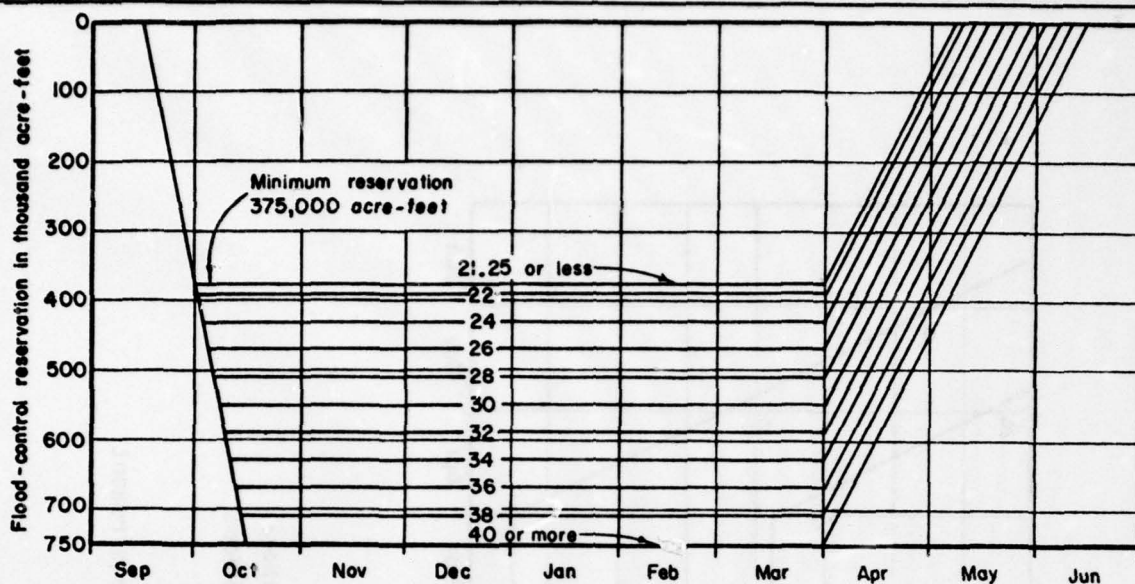
USE OF DIAGRAM

1. Parameters are preceding 60-day basin-mean precipitation expressed as a percentage of normal annual precipitation.

2. Except when releases are governed by the emergency release diagram, all storage in excess of that indicated by this diagram shall be released as rapidly as possible, subject to the following conditions:

   a. That releases do not exceed 50,000 cfs or maximum rate of inflow for the flood, whichever is greater.

   b. That releases do not exceed 150,000 cfs at any time.

   c. That flows in a downstream damage reach do not exceed 180,000 cfs at any time.

   d. That releases are not increased more than 10,000 cfs or decreased more than 5,000 cfs in any 2-hour period.

NOTE: After 31 March, reservation for any given parameter decreases 10,000 acre-feet per day.

Fig. 7.05. Flood-control diagram

forecasted flood, with appropriate contingency allowances, and yet completely fill the reservoir whenever possible.

The limiting amount of space dedicated to the control of snowmelt floods can ordinarily be determined by routings of design and maximum recorded floods. It is usually found that full snowmelt space may be utilized during the early months of the snowmelt season but that it is ordinarily safe to reduce the maximum space during the later months, because the full space could never be effectively utilized at these later dates. Important exceptions to this rule occur in cases where reservoir capacity is small relative to runoff volume or where a reservoir is located at high elevations where melting occurs later. The standard project snow-melt flood usually involves early high melt rates, and does not ordinarily require large amounts of reservoir space late in the season, because snow pack conducive to high melt rates is not great enough to sustain high runoff late in the season. Accordingly, some major observed flood will ordinarily govern during the later months.

Section 7.05. Drawdown Limitations

The multiple use of reservoir space will require drawdown of reservoir stages at the beginning of the flood season or when any flood-potential index values used might result in increased space requirement. In formulating flood control regulations for the multiple use of reservoir space, consideration should be given to the effects of necessary drawdown of reservoir stages when inflows are below flood stage. If some damages are caused by releases during the drawdown periods, a claim

7-11

might be made that they have been caused unnecessarily, and consequences might result that would seriously impair future operation. Accordingly, drawdown rates should be maintained at nondamaging rates insofar as possible, and the regulations should make full allowances for the time required to evacuate space at these safe rates, with liberal allowance for possible inflow rates at the time. Drawdown requirements are usually determined by routing the design flood preceded by maximum observed runoff considered to be reasonably consistent with design-flood conditions.

CHAPTER 8. CONDITIONAL RAIN-FLOOD RESERVATION

Section 8.01. Nature and Limitations

Experience has indicated that rain storms and rain floods in many cases cannot be forecasted accurately enough nor sufficiently in advance for firm use of forecasts in reservoir operation criteria. While continuous efforts should ordinarily be made to forecast rain floods whenever and wherever appropriate in connection with reservoir operation, it is often considered to be unsafe to depend on the evacuation of reservoir space on the basis of a rainstorm or rain-flood forecast. However, there are times when ground conditions are such that the rain-flood potential is materially below normal and others when the potential is materially above normal, and it is often possible to increase overall project accomplishments by varying the required flood-control space with the conditions of the ground. If the ground is dry at the beginning of a storm, loss rates will in most cases be high, and the resulting flood will be less severe than otherwise, even though the ground becomes progressively wetter during the storm. However, as soon as a storm occurring on dry ground is over, the ground is wet, and provision should be made immediately to evacuate such additional space as is considered necessary to control a flood resulting from the project design storm occurring on the wetter ground.

When it is proposed, in formulating regulations, to reduce the space requirement because of dry ground, it must be ascertained that space can

8-01

be subsequently evacuated in time to provide the additional space required when the ground becomes wet. This is possible only in cases where release rates are adequate to evacuate space during a series of moderate floods that might precede the main design flood period. Whether this is possible can be determined roughly by estimating the critical duration of design runoff, which is defined herein as the time between the beginning of storage of flows in excess of flood releases and the time of maximum reservoir stage. If the critical duration of runoff is a few days or less, the reservoir is most likely to be filled by a single rain flood of a few days duration, and since ground conditions at the beginning of that flood would ordinarily influence the flood magnitude, space requirement could be a function of ground conditions. On the other hand, if the critical duration of runoff is greater than a few days, the reservoir is most likely to be filled by a sequence of floods, and although the ground may be dry at the beginning of the sequence, it becomes wet after the first storm or two, and the remaining storms occur on wet ground. Consequently, ground conditions probably would not greatly influence space requirements where critical durations are long. If the critical duration exceeds 5 days, it is ordinarily not wise to permit conditional storage in the rain-flood space.

Section 8.02. Selection of Index

A practical index of ground conditions is the preceding 60-day basin-mean precipitation. Although this index is not the most accurate measure of ground wetness and has theoretical weaknesses, practical

operation advantages discussed below normally override these handicaps. Nonetheless, since each basin has its own peculiarities, it may be desirable to select alternative indexes in some cases. The 60-day precipitation index for each reservoir area is computed from daily reports provided by the network of precipitation stations covering that area. Since the number of stations usable is limited, this computation is only approximate, and efforts should be made to obtain reports from as many well-distributed stations as feasible. Where precipitation is primarily orographic, precipitation amounts vary systematically with the topography of each basin. Consequently a simple arithmetic mean of all reporting stations may differ significantly from the true basin mean. A more satisfactory system is to use the ratio of the normal annual precipitation at each station to the normal annual basin-mean precipitation. Under this system, the sum of the short-term precipitation values at all reporting stations is divided by the sum of the normal annual precipitation values for the same stations to obtain the average proportion of normal annual precipitation that fell on the basin during the period, and this average proportion is multiplied by the normal annual basin-mean precipitation to estimate the short-term basin-mean value. Under this system, temporary failure of some of the stations to report or permanent changes in the location of stations which make up the network will not significantly affect the computation of basin-mean precipitation. Volume 4 of this report contains a more complete discussion on the computation of basin-mean precipitation.

Studies have been made of various other indexes such as preceding runoff for various durations, preceding precipitation since the beginning

of the season or for various durations, preceding precipitation with greater weight given to the more recent amounts, and various other more complex indexes. A typical correlation study relating runoff to storm precipitation and ground-wetness index resulted in the following correlation coefficients:

Ground-Wetness Index	Correlation Coefficient
Preceding 15-day precipitation	.53
Preceding 30-day precipitation	.55
Preceding 60-day precipitation	.64
Weighted 15-, 30-, 60-day precipitation	.62
Preceding precipitation since 1 October	.62
Preceding 15-day runoff	.62
Preceding 30-day runoff	.66
Preceding 60-day runoff	.65
Weighted 15-, 30-, 60-day runoff	.64
Preceding runoff since 1 October	.61
Precipitation minus runoff depth since 1 Oct.	.59

In general, preceding runoff appears to be the most accurate index, but preceding precipitation is almost as accurate. It is considered that the precipitation index is more generally satisfactory, because its influence is registered earlier. The duration of preceding precipitation used for the index should be sufficiently long so that fluctuations of the index will not cause excessive operational hardships such as forcing release of valuable water at frequent intervals. While it may be theoretically desirable, it is not satisfactory to give greater weight to the most recent quantities, because this would result in unnecessarily rapid fluctuations of the index and consequent difficulty in operation.

Considering all aspects of this problem, 60-day precipitation has been
found to be a generally satisfactory index.

Section 8.03. Variation of Space Requirement

When including provisions in the operation regulations to use flood
control space for conservation purposes during periods of dry ground
conditions, it is necessary to select some measure of the effect of
ground conditions on space requirements. The selected index (for example,
preceding 60-day precipitation as discussed in the preceding paragraph)
must be related to loss-rate criteria, and these criteria in turn must
be applied to a design or other hypothetical storm in order to determine
the space required to control the resulting flood. This is accomplished
by plotting infiltration index or some other measure of loss rates against
an observed ground wetness index for historical floods as illustrated in
fig. 7.03. A line enveloping loss rates on the lower side would then be
selected for project design, as shown in fig. 7.03, because project oper-
ation must be adequate to control floods when the more adverse observed
ground conditions occur.

An index value for dry ground conditions should then be selected,
and a corresponding loss-rate curve derived, usually from hydrograph
analysis of a specific recorded flood. These loss rates could then be
applied to the design storm and to various percentages of the design
storm to determine space requirements under dry ground conditions for
various times of the year.

Space requirements for intermediate conditions between dry and wet ground can be interpolated linearly for all practical purposes. It is best to select a firm minimum space for dry ground conditions equal to at least half of the maximum space required for wet ground conditions during the main part of the rain-flood season. An illustration of the construction of a diagram using these principles, based on data in figs. 7.03 and 7.04, is shown in fig. 7.05.

Before adopting a flood-control diagram derived as above, all important historical floods should be routed and the space requirement and wetness index plotted on the diagram at appropriate points before the start of flood flows requiring storage. Parameters determined from hypothetical considerations should then be adjusted if necessary to provide at least as much storage as that required by the historical floods. If the hypothetical parameters require excessive storage reservation in comparison with that required by historical floods resulting from storms approaching design magnitude, they should be adjusted to require a reasonable margin of storage above that required by such historical floods.

Section 8.04. Effect on the Control of Rain Floods

The conditional use of flood control space reduces the flood control accomplishment to some extent unless a compensating increase in maximum flood control space is made. When rain-flood parameters are used, the diagram provides for control of a specific design storm on whatever ground conditions might exist rather than of a specific design flood. If a 50-year protection is to be provided by conditional use of space, for

example, the maximum space needed is that required to control a flood
from the 50-year storm on very wet ground. If 50-year protection is
to be provided by firm use of flood control space, on the other hand,
the maximum space needed is that required to control 50-year runoff, and
this would be somewhat less.

CHAPTER 9. CONDITIONAL SNOWMELT-FLOOD RESERVATION

Section 9.01. Snowmelt Forecast

Inasmuch as seasonal snowmelt runoff volumes can ordinarily be
forecasted months in advance with a reasonable degree of reliability, an
excellent opportunity exists for both providing adequate flood control
space as needed, and for subsequently providing conservation storage in
the reservoir whenever possible.

Forecasts of the total runoff can be made at the beginning of each
month (and at intermediate dates, where warranted) largely on the basis
of field measurement of snow on the ground by means of a snow course net-
work. The accuracy of these total volume forecasts increases progressively
as the season advances. Before the middle of the snowpack accumulation
season, the possible error is very large, because it must include not
only an estimate of the runoff expected from snow on the ground but also
a forecast of the additional snow that may fall in the last half of the
season. By the end of the accumulation season, this second source of
error has become comparatively small, and the overall accuracy increases
markedly.

After most of the snow has melted, other types of information become
available, such as the magnitude and rate of decrease of the snow-covered
area, magnitude and rate of change of the runoff yield per degree-day of
temperature at key weather stations, and finally, rate of recession of
the snowmelt runoff at stream gaging stations. By use of these additional

9-01

types of data, forecasts can be made of the remaining runoff which have considerably greater accuracy than could be achieved by simply subtracting the observed runoff volume since the start of the snowmelt season from the total forecast volume.

Section 9.02. Latitude of Operation

Since the accuracy of snowmelt forecasts generally increases as the season progresses, it is desirable that regulations should provide for deferring flood releases until a surplus of water above that needed for conservation or power purposes is assured or until the available space plus project releases throughout the remainder of the critical melt period is required to control the anticipated floodwaters plus a contingency allowance. In this way, releases that might impair project objectives would be based on the best available forecast, since forecast reliability continuously improves during the snowmelt season. If after initiating flood releases, the runoff forecast is diminished, flood releases can then be stopped or reduced, and the effect of the earlier forecast error can be largely or completely nullified. Thus the latitude available in operating for snowmelt floods is equal to the flood release rate (excess above release for other purposes) multiplied by the amount of time until the reservoir is expected to fill. This latitude of operation ordinarily makes it possible to control anticipated floods without seriously risking the possibility of not filling the reservoir for conservation or power purposes.

9-02

Section 9.03. Forecasted Space Requirement

In constructing a flood control diagram for the control of snow-melt floods, the space requirement corresponding to a specified volume of remaining runoff after a given date is determined by routing of historical runoff between that date each year and the date that reservoir storage would be maximum. The space requirement is then plotted against the total observed runoff for the forecast period. A set of curves thus derived is illustrated in fig. 9.01. These curves can be used to determine space requirement corresponding to any specified volume of remaining runoff.

Section 9.04. Standard Error of Estimate

In formulating parameter lines for snowmelt operation, allowance must be made for forecast errors and other contingencies. A measure of normal forecast error can be obtained by examining past forecast exper-ience and computing the "standard error of forecast" from the actual historical forecasts. If a new forecast method is to be used, the standard error should be obtained by applying the procedure to historical data, taking care not to use data that would not be available at the date of forecast. The standard error of forecast is computed by adding the squares of forecast errors and dividing by the number of statistical degrees of freedom, F (approximately equal to the number, N, of forecast errors used). The square root of the quotient thus obtained is the standard error of forecast, S_e.
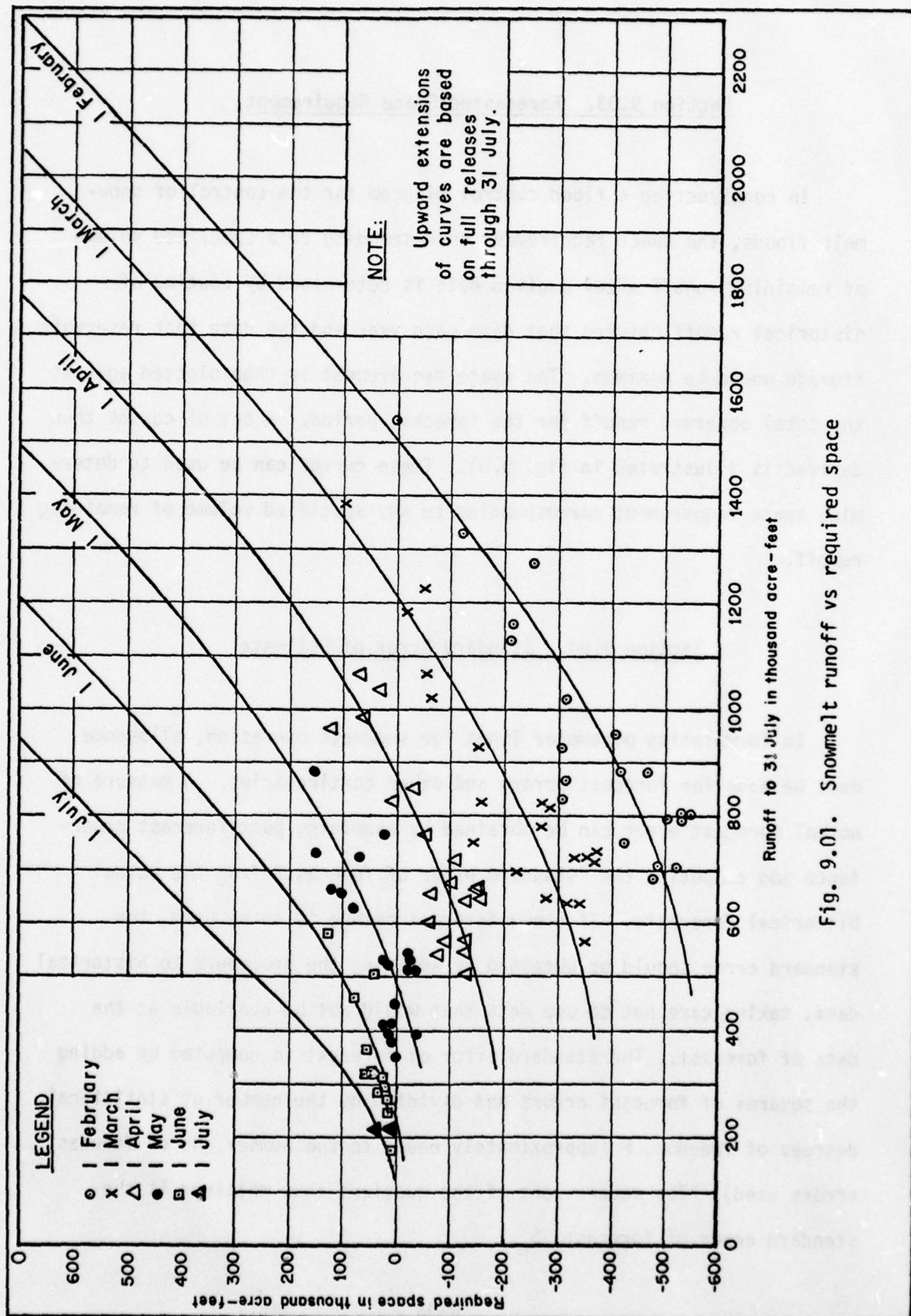
Fig. 9.01. Snowmelt runoff vs required space

If X' is the forecast and X the observed quantity, the equation would be as follows:

$$S_e^2 = \frac{\Sigma(X' - X)^2}{F} \qquad (9-1)$$

In addition to the forecast error of total runoff volume, there is an uncertainty of future weather conditions and as to whether runoff will be unusually early or late. In the event of an unusually early runoff, more flood control space is required because there is less time for making releases. A measure of this uncertainty is the standard error of the space-runoff relationship, which is the standard deviation of points about the lines in fig. 9.01, measured in the horizontal direction. This standard error, called herein the "standard error of timing," can be combined with the standard error of forecast by taking the square root of the sum of the squares of these two quantities. The result is called herein the "standard error of estimate." Table 9.01 and fig. 9.02 illustrate the typical relation between the various types of errors and the forecast rate.

Section 9.05. Error Allowance

The multiple (k) of that standard error of estimate to be added as an error allowance will depend on the seriousness of losing control of a snow-melt flood, the importance of filling the reservoir for conservation, and the latitude of operation discussed above. Commonly, twice the standard error of estimate is used, because this assures control in a high percentage of years and ordinarily represents a reasonable compromise between

Table 9.01. Forecast verification data
natural April-July flows

(Values in thousand acre-feet)

Year	Recorded flow	1 February Forecast	Error	1 March Forecast	Error	1 April Forecast	Error	1 May Forecast	Error
1932	569					557	- 12		
1933	362					390	28		
1934	138								
1935	501								
1936	598					646	48		
1937	545					630	85	630	85
1938	850					700	-150	700	-150
1939	220					280	58	225	3
1940	516					400	-116	400	-116
1941	600					550	- 50	560	- 40
1942	665					500	-165	550	-115
1943	541					570	29	570	29
1944	346					380	34	380	34
1945	507					500	- 7	425	- 82
1946	448					550	102	500	52
1947	254					325	71	300	46
1948	526					260	-266	410	-116
1949	439					500	61	440	1
1950	569					575	6	610	41
1951	351					250	-101	250	-101
1952	967					1050	83	1000	33
1953	482	600	118	460	- 22	400	- 82	430	- 52
1954	378	390	12	370	- 8	400	22	380	2
1955	348	500	152	430	82	300	- 48	360	12
1956	642	900	258	800	158	620	- 22	675	33
1957	420	385	- 35	335	- 85	355	- 65	345	- 75
1958	827	460	-367	490	-337	830	3	790	- 37
Average			157		115		68		51
Extreme			-367		-337		-266		-150

9-06
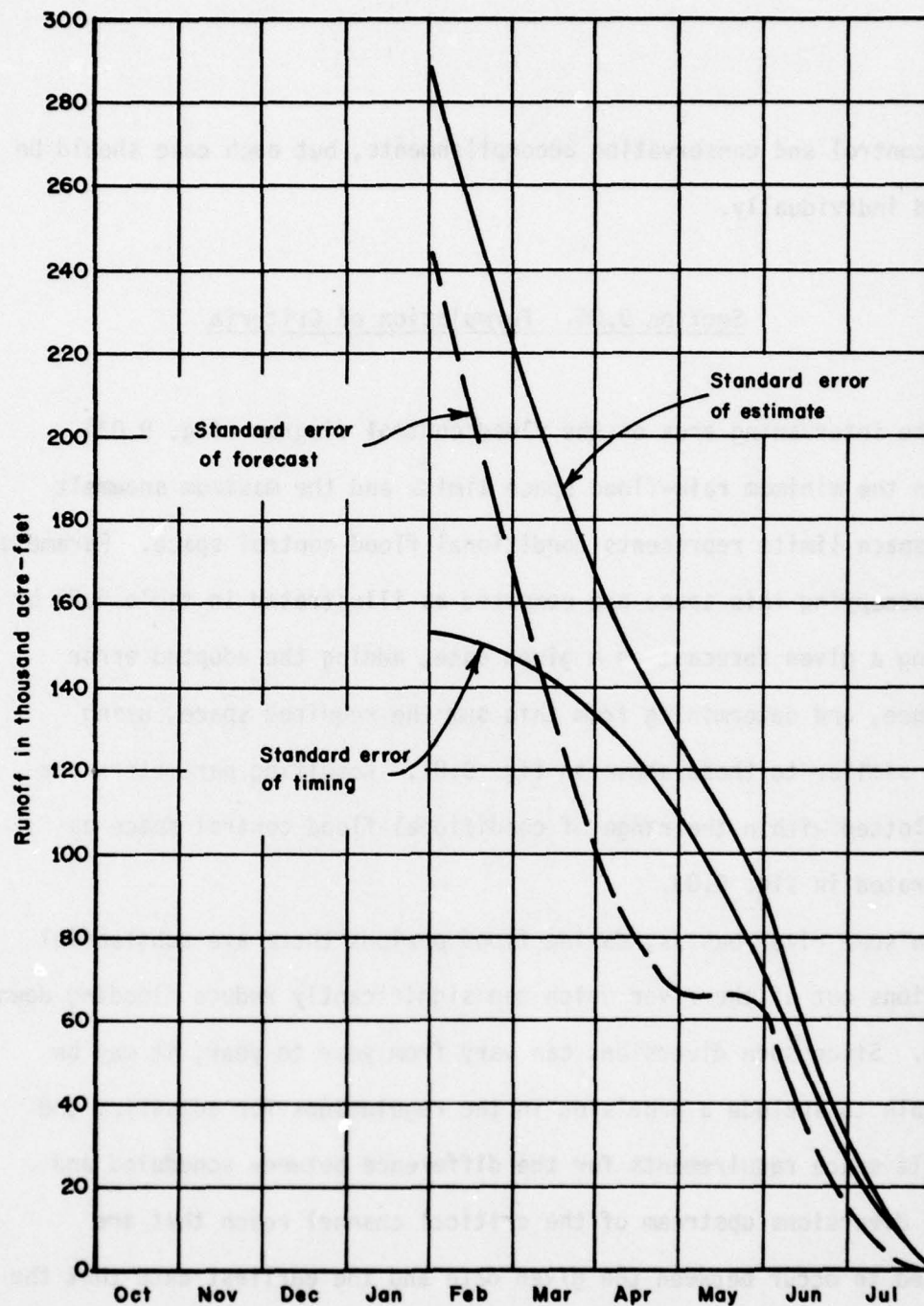
Fig. 9.02.   Standard errors of estimating
snowmelt runoff

flood control and conservation accomplishments, but each case should be studied individually.

Section 9.06.   Formulation of Criteria

The intervening area on the flood control diagram (fig. 9.03) between the minimum rain-flood space limits and the maximum snowmelt flood space limits represents conditional flood control space. Parameter lines occupying this space are computed as illustrated in table 9.02 by assuming a given forecast on a given date, adding the adopted error allowance, and determining from this sum the required space, using curves similar to those shown in fig. 9.01. Resulting parameters are then plotted within the range of conditional flood control space as illustrated in fig. 9.03.

In some river basins, during flood periods there are substantial diversions out of the river which can significantly reduce flooding down-stream. Since such diversions can vary from year to year, it may be desirable to include a provision in the regulations for adjusting the snowmelt space requirements for the difference between scheduled and normal diversions upstream of the critical channel reach that are expected to occur between the given date and the earliest date that the reservoir can fill under full flood control releases. Experience has shown that scheduled diversions cannot be fully depended upon, and it may be well to provide for only about 80 percent of the computed difference.
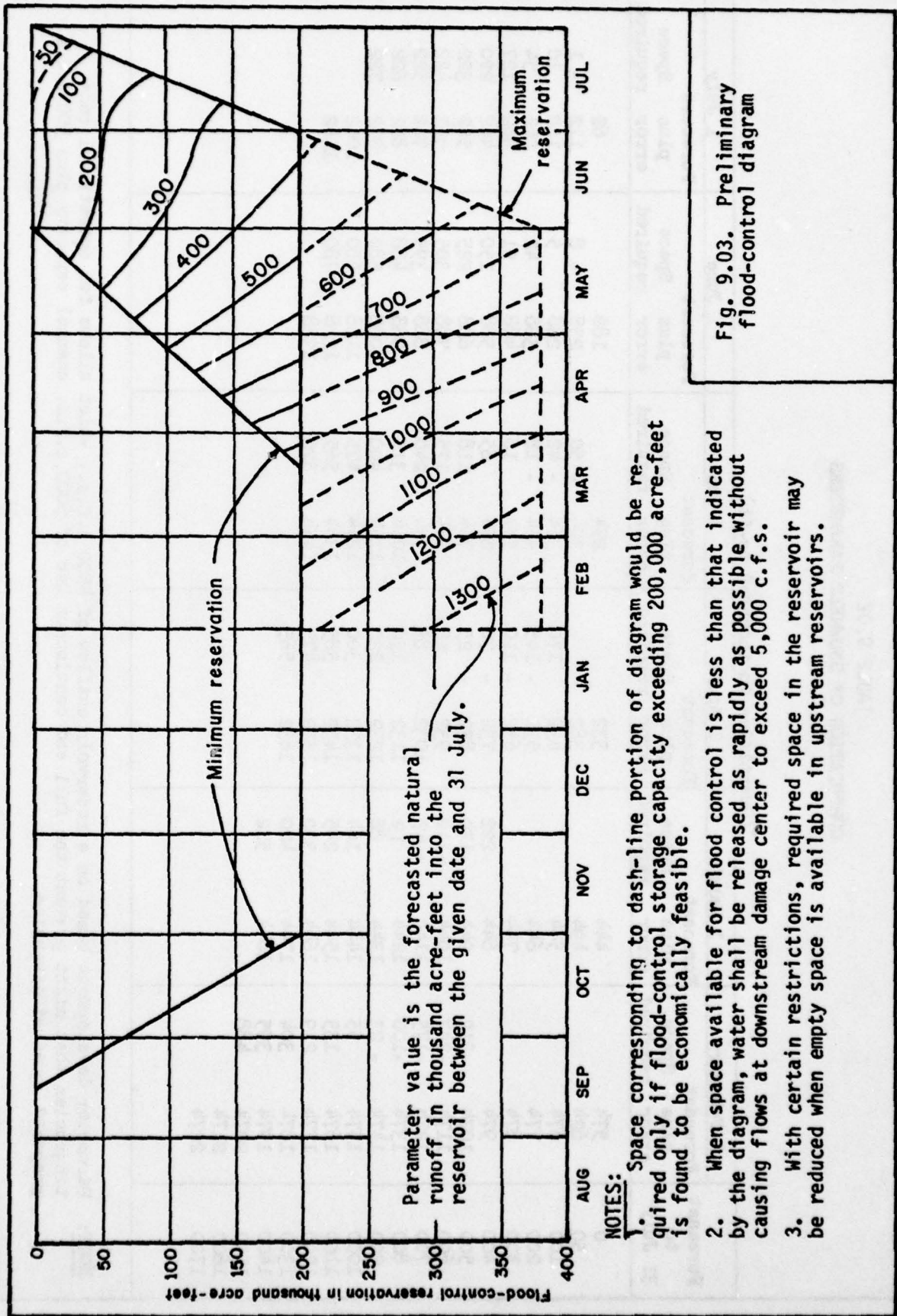
Fig. 9.03. Preliminary flood-control diagram

Flood-control reservation in thousand acre-feet

Maximum reservation

Minimum reservation

Parameter value is the forecasted natural runoff in thousand acre-feet into the reservoir between the given date and 31 July.

NOTES:

1. Space corresponding to dash-line portion of diagram would be required only if flood-control storage capacity exceeding 200,000 acre-feet is found to be economically feasible.

2. When space available for flood control is less than that indicated by the diagram, water shall be released as rapidly as possible without causing flows at downstream damage center to exceed 5,000 c.f.s.

3. With certain restrictions, required space in the reservoir may be reduced when empty space is available in upstream reservoirs.

TABLE 9.02

COMPUTATION OF SNOWMELT PARAMETERS

(Quantities in thousand ac-ft)

Forecast to 31 July	1 February Forecast plus error	1 February Space required	1 March Forecast plus error	1 March Space required	1 April Forecast plus error	1 April Space required	1 May Forecast plus error	1 May Space required	1 June Forecast plus error	1 June Space required	1 July Forecast plus error	1 July Space required
0	574		444		332		254	-50	188	-8	62	-1
50	624		494		382		304	-42	238	5	112	10
100	674		544		432	-170	354	-18	288	42	162	54
200	774		644		532	-145	454	18	388	91	262	127
300	874		744	-222	632	-110	554	65	488	150	362	220
400	974		844	-170	732	-70	654	118	588	225	462	322
500	1074	-312	944	-110	832	-25	754	175	688	305	562	422
600	1174	-247	1044	-47	932	25	854	240	788	395	662	522
700	1274	-175	1144	19	1032	85	954	315	888	488	762	622
800	1374	-100	1244	88	1132	150	1054	400	988	580	862	722
900	1474	-23	1344	164	1232	220	1154	475	1088	680	962	
1000	1574	55	1444	245	1332	300	1254	565	1188	780	1062	
1100	1674	135	1544	330	1432	385	1354	670	1288		1162	
1200	1774	219	1644	420	1532	475	1454		1388			
1300	1874	304	1744	512	1632	565						
1400	1974	395	1844									
1500	2074	488										
1600	2174											
1700	2274											

NOTE: Parameter development based on a reservoir outflow of 4500 c.f.s., which allows for operational contingencies that might prevent the full and continuous use of 5000 c.f.s. channel capacity plus 500 c.f.s. proposed aqueduct diversion.

Section 9.07. Effect on the Control of Snowmelt Floods

It should be recognized that when flood control space is reserved on a forecast or conditional basis, the space provided will occasionally be inadequate for flood control or too large to fill for conservation purposes, because of forecast and model imperfections. This should be reflected in the project frequency curves by discounting the amount of flood control space that can be depended upon when evaluating benefits.

CHAPTER 10. MULTIPLE-RESERVOIR OPERATION

Section 10.01. General

Various problems arise when more than one reservoir in a system is operated for flood control or when reservoirs operated for other purposes can influence inflows to or releases from a reservoir operated for flood control. Where different reservoirs in a system subject to flood control regulations are operated for flood control by different agencies, the regulations should be worded so that coordination of the flood control operation is assured without requiring any party to operate beyond his capacity or to the undue detriment of other functions. Each operator should be given maximum flexibility of operation consistent with attainment of flood control objectives. The general procedures for coordinating flood control operation and for making allowances for incidental flood control effects by reservoirs operated for other purposes are discussed in the following paragraphs.

Section 10.02. Incidental Regulation by Conservation Reservoirs

In cases where reservoirs not operating for flood control are located upstream from a flood control reservoir, it is generally best to establish a basic flood control diagram for the flood control reservoir on the assumption that no upstream storage space will exist and, if appropriate, to provide criteria allowing for the assured beneficial effects of these

10-01

upstream reservoirs. Beneficial effects are assured when:

<u>a</u>. Empty space exists at the beginning of a flood.

<u>b</u>. Dependable release criteria guarantee that excess water will be
stored in that reservoir.

<u>c</u>. If a flood capable of filling the flood control reservoir occurs,
a sufficient proportion of the runoff will occur above the upstream reser-
voir to fill it.

Water storable at the upstream reservoir can be estimated as illus-
trated by curve a of fig. 10.01, the development of which is described
in section 10.03. A conservative enveloping technique that would represent
minimum runoff at the upstream reservoir should be used. In order to allow
for unforseen contingencies, it may be wise to take credit for not more
than about 80 percent of the portion of the actual and usable upstream
storage space not governed by flood control regulations. Where storage
quantities in upstream reservoirs can change rapidly, adequate communi-
cation should exist in order to assure that the space believed to be
available actually does exist at the time.

In the case of a conservation reservoir located downstream from the
flood control reservoir, no flood control allowance for the empty space
can ordinarily be made, since flood control releases are not required at
the downstream reservoir when water is stored within that space. The
downstream reservoir will usually fill early and then provide no storage
during the main part of the flood.
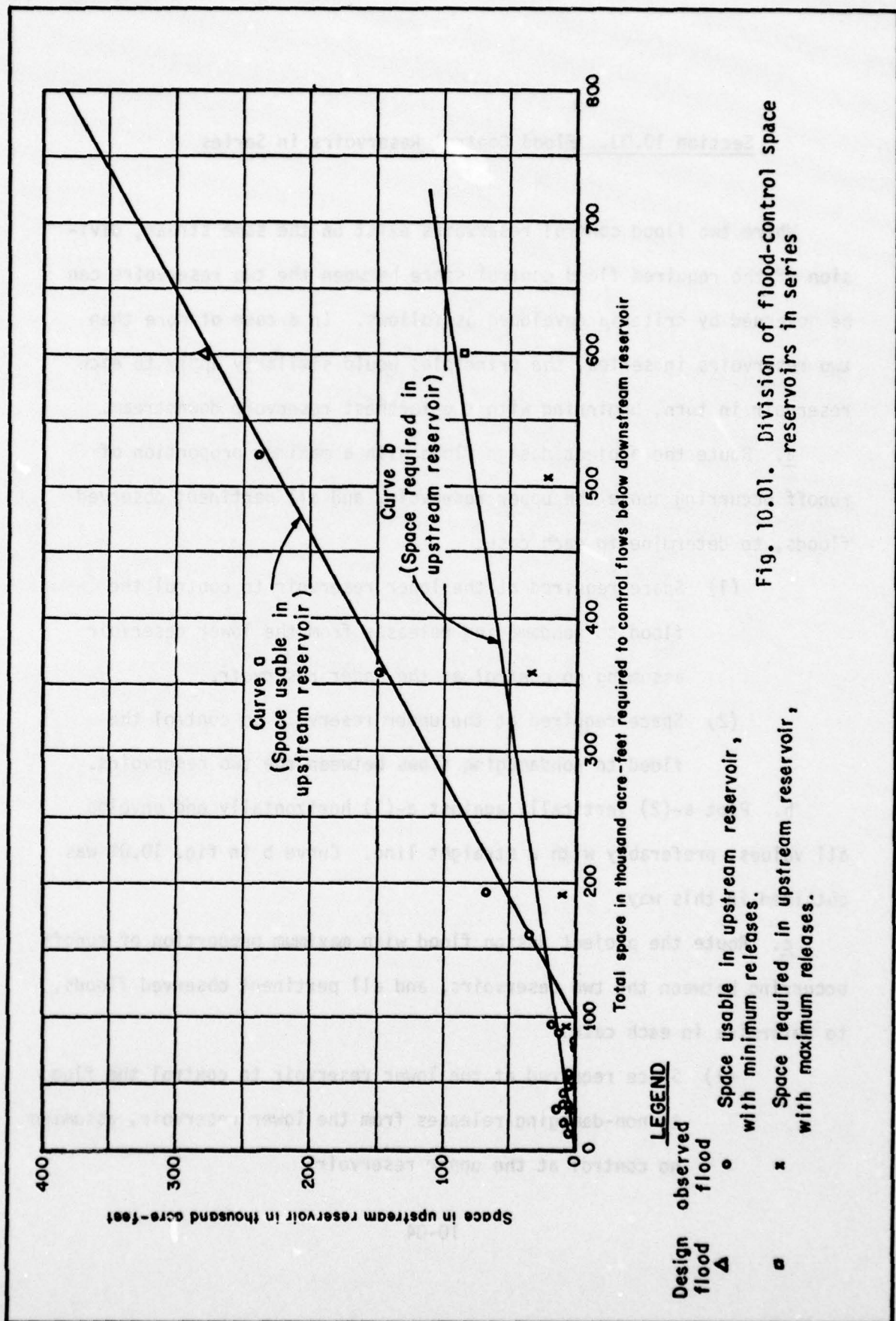
Fig. 10.01. Division of flood-control space required to control flows below downstream reservoir, reservoirs in series

LEGEND

Design observed flood	△	
○	Space usable in upstream reservoir, with minimum releases.	
×	Space required in upstream reservoir, with maximum releases.	

Curve a (Space usable in upstream reservoir)

Curve b (Space required in upstream reservoir)

Space in upstream reservoir in thousand acre-feet

Total space in thousand acre-feet required to control flows below downstream reservoir

Section 10.03. Flood Control Reservoirs in Series

Where two flood control reservoirs exist on the same stream, division of the required flood control space between the two reservoirs can be governed by criteria developed as follows. In a case of more than two reservoirs in series, the principles would similarly apply to each reservoir in turn, beginning with the farthest reservoir downstream.

<u>a</u>. Route the project design flood with a maximum proportion of runoff occurring above the upper reservoir, and all pertinent observed floods, to determine in each case:

    (1) Space required at the lower reservoir to control the flood to nondamaging releases from the lower reservoir assuming no control at the upper reservoir.

    (2) Space required at the upper reservoir to control the flood to nondamaging flows between the two reservoirs.

<u>b</u>. Plot a-(2) vertically against a-(1) horizontally and envelop all values, preferably with a straight line. Curve b in fig. 10.01 was obtained in this way.

<u>c</u>. Route the project design flood with maximum proportion of runoff occurring between the two reservoirs, and all pertinent observed floods, to determine in each case:

    (1) Space required at the lower reservoir to control the flood to non-damaging releases from the lower reservoir, assuming no control at the upper reservoir.

(2) Space usable (water storable) at the upper reservoir if
minimum permissible releases are maintained at the upper
reservoir.

d. Plot c-(2) vertically against c-(1) horizontally and envelop
on the lower side, preferably with a straight line. Curve a in fig. 10.01
was obtained in this way.

Space required in the upper reservoir is that indicated by curve b
of fig. 10.01. Space required in the lower reservoir is the difference
between total required space and that available in the upper reservoir,
except that credit for space in the upper reservoir will be limited to
that indicated by curve a. For example, if the total storage requirement
for the two reservoirs were 600,000 acre-feet, a storage of about 90,000
acre-feet (curve b) would be required for the upper reservoir and 275,000
acre-feet (curve a) would be usable at the upper reservoir. If, in fact,
the upstream reservoir had an available storage of 200,000 acre-feet, the
storage required at the lower reservoir would be 600,000 - 200,000 or
400,000 acre-feet.

If channel capacity constraints between the two reservoirs are such
that a relatively large amount of storage is required at the upstream
reservoir to prevent flooding between the reservoirs, it is possible that
curve b (fig. 10.01) will plot above curve a. In this case, curve b would
dictate the storage in the upper reservoir, and required storage at the
lower reservoir would equal the total storage minus the usable storage
at the upper reservoir. The combined storage of the two reservoirs would
exceed the "total" storage.

Where no damages occur between the two reservoirs, and with unlimited outlet capacity at the upper reservoir, curve b in fig. 10.01 will show a zero space requirement for the upper reservoir. In this case, minimum releases would normally be made at the upper reservoir and maximum space would be reserved in the lower reservoir. However, releases from the two reservoirs should be scheduled so that whenever flood control space is occupied, the remaining empty space will generally be divided between the two reservoirs, insofar as possible within the range of proportion determined in subparagraphs b and d above. However, in cases where releases from the downstream reservoir are controlled by the outlet capacity at that dam, an effort should be made to maintain the stage as high as feasible and necessary in the lower reservoirs in order to maintain higher head on the outlets and thus make higher flood releases possible.

Section 10.04. Flood Control Reservoirs in Parallel

Where two flood control reservoirs exist on separate streams tributary to a single stream where flood damages occur, and where it is economically and hydrologically feasible to fully coordinate the operation of the two reservoirs, division of the required flood control space between the two reservoirs can be governed by criteria developed as follows:

a. Route the project design flood with maximum proportion of runoff occurring above reservoir A, and all pertinent recorded floods, with maximum feasible nondamaging releases from reservoir A and the remainder of nondamaging releases from reservoir B, to determine minimum space

requirement at reservoir A. Plot space required at A versus total space required, and envelop the plotted points, preferably with a straight line.

b. Route the project design flood with maximum proportion of runoff occurring above reservoir B, and all pertinent recorded floods, with maximum feasible nondamaging releases from reservoir B and the remainder of nondamaging releases at reservoir A to determine space usable at reservoir A. Plot space usable at A versus total space required and envelop on the lower side, preferably with a straight line.

c. The proportion of total required space that should be located in reservoir A is intermediate between these two envelope curves, and should generally remain a flexible amount where operational flexibility is desirable. The difference between the total required space and that usable in reservoir A is the minimum required in reservoir B. Similarly, the difference between the total required space and that required in reservoir A is that usable in reservoir B.

d. Releases from the two reservoirs should be scheduled so that whenever flood control space is occupied, the remaining empty space will be divided between the two reservoirs, insofar as possible, within the range of proportion indicated in c above.

Section 10.05. Index Levels and the Equivalent Reservoir Concept

In simulating the operation of a reservoir system, it has been found useful to employ concepts of "index levels" and "equivalent reservoirs" for determining release priorities among reservoirs. Index levels are

integer numbers assigned to certain elevations in a reservoir. The levels are assigned in such a way as to control the "balancing" of the reservoir system. A system is "in balance" when all reservoirs are at the same index level. The level of a given reservoir at a given point in time is obtained by linear interpolation in a table of index levels versus storage for the reservoir. In balancing levels among reservoirs, priority for releases is governed by the criteria that reservoirs at the highest levels at a given point in time are given first priority for making releases. Exhibit 4 in Appendix 1 illustrates how index levels can be chosen to control operation rules for a reservoir system. Procedures in section 10.03 and 10.04 can be useful in establishing the amount of storage in each reservoir for each index level.

In determining the priority of reservoir releases among parallel reservoirs, or among subsystems of a reservoir system, the concept of an "equivalent reservoir" is used. For example, consider a situation in which two parallel reservoirs are upstream from a third, as shown in fig. 10.02. Table 10.01 shows level-storage characteristics for a reservoir equivalent to the three reservoirs.

Suppose that it is desired to determine the amount of release to make from reservoirs 1 and 2 and that storages in reservoirs 1, 2 and 3 at the end of the previous time period are 35, 12.5 and 3, respectively. For these storages, the equivalent reservoir storage is 50.5 and the equivalent level is 3.97. The levels of reservoirs 1, 2 and 3 are 4.5, 3.5 and 2.5, respectively. A criteria that could be used to control releases is that releases will be made from an upstream reservoir (reservoir 1 or 2) if its level is above the greater of the level of reservoir 3 or the

Reservoir 1   Reservoir 2
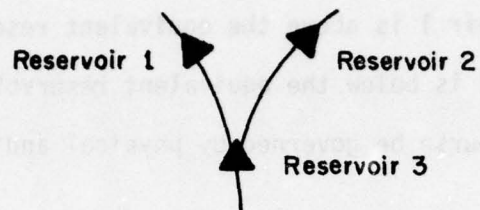
Reservoir 3

Fig. 10.02. Reservoir configuration for
equivalent reservoir example

Cumulative Storage - Acre Feet				
Index Level	Reservoir 1	Reservoir 2	Reservoir 3	Equivalent Reservoir
5	40	20	8	68
4	30	15	6	51
3	20	10	4	34
2	10	5	2	17
1	0	0	0	0

Table 10.01. Equivalent reservoir level-
storage characteristics

equivalent reservoir level (reservoirs 1, 2 and 3). Therefore, a release would be made from reservoir 1 and not from reservoir 2 because the level of reservoir 1 is above the equivalent reservoir level and the level of reservoir 2 is below the equivalent reservoir level. The actual releases would of course be governed by physical and other constraints that must be met.

Computer program HEC-5C, which is described in detail in Appendix 1, uses both the index level and equivalent reservoir concepts in simulating operation of reservoir systems.

CHAPTER 11. OPERATION COMPROMISE FOR RAINFLOODS

Section 11.01. Operation Conflicts

There is practically no case of multiple use of reservoir space
where the accomplishment of one objective does not interfere to some
extent with the accomplishment of other objectives. Since there is in
all cases a conflict of interest, there is sometimes the temptation to
depart from flood control regulations in the interest of other objectives,
particularly irrigation and power generation. The temptation to infringe
on flood control space is sometimes strong, because usually losses to
other functions are obvious, and losses to flood control (although poten-
tially much greater) may not occur or indeed probably will not occur in
any particular case. Consequently, a very rigid attitude against infringe-
ment on flood control space must be maintained at all times. However, when
the flood control rules are formulated, it must be recognized that there
are certain periods in the year when the probability of floods is low and
the value of space for other purposes is particularly high, and consider-
ation should be given to reducing the flood control requirements during
these periods and increasing them at other times.

Section 11.02. Early Filling Requirements

In many cases, provision of the full flood control space until the
end of the rain-flood season will prevent the use of such space during the

non-flood season for other purposes. Generally this occurs where there is very little runoff after the end of the flood season. In these cases a reduction in the required flood control space toward the end of the season can be considered, but the reduction should be minor if assured flood protection is to be obtained. There have been many disastrous consequences of too-early reservoir filling. A suggested rule to follow is to diminish normal flood control requirements only where the additional space is required and more beneficial for other purposes, but to provide on any date at least two-thirds of the flood control space that would be required for that day by normal flood control criteria. A means of compensating for such reduction of space requirement is suggested below.

Section 11.03. Delayed Drawdown

For the beginning of a flood season, it may be desirable to incorporate in the diagram a moderate reservoir drawdown provision that would result in emptying the flood control space at a later date than that required for full flood protection, in order to increase the effective use of the released water. Decisions to do this should be based on principles and considerations discussed in the preceding paragraph. Reduction should generally not be made unless important conservation benefits are thereby obtained and should not be made to the extent that would seriously impair assured flood protection.

Section 11.04. Transition Operation

The nature of flood control rules is ordinarily such that flood releases are often not required until it is estimated that full releases should be continued until the flood terminates. This minimizes the possibility of wasting water unnecessarily. If transition criteria between normal conservation operation and flood control operation are considered necessary, they should be incorporated into the rules, and the required flood control space would thereby be increased. Where releases over and above normal conservation uses can be utilized, consideration should be given to releasing at intermediate rates during periods when a surplus of water is apparent and maximum flood control releases are not yet required. (In the case of snowmelt runoff that can be forecast far in advance, this can be accomplished by a separate set of parameters based on releases at a specified intermediate rate between any given date and the date the reservoir is expected to fill.)

After flood waters have been stored in a reservoir where high release rates are employed, it is necessary to plan the reduction of the releases so that they will be reduced to conservation rates by the time the flood control space has been evacuated, without exceeding the safe rate of reduction. This can be done by constructing a set of curves similar to those shown in fig. 11.01 as follows:

a. Determine a safe rate of reduction of flood release for various release rates. This should usually be such that the rate of fall of downstream river stages will be somewhat less than the maximum observed rate
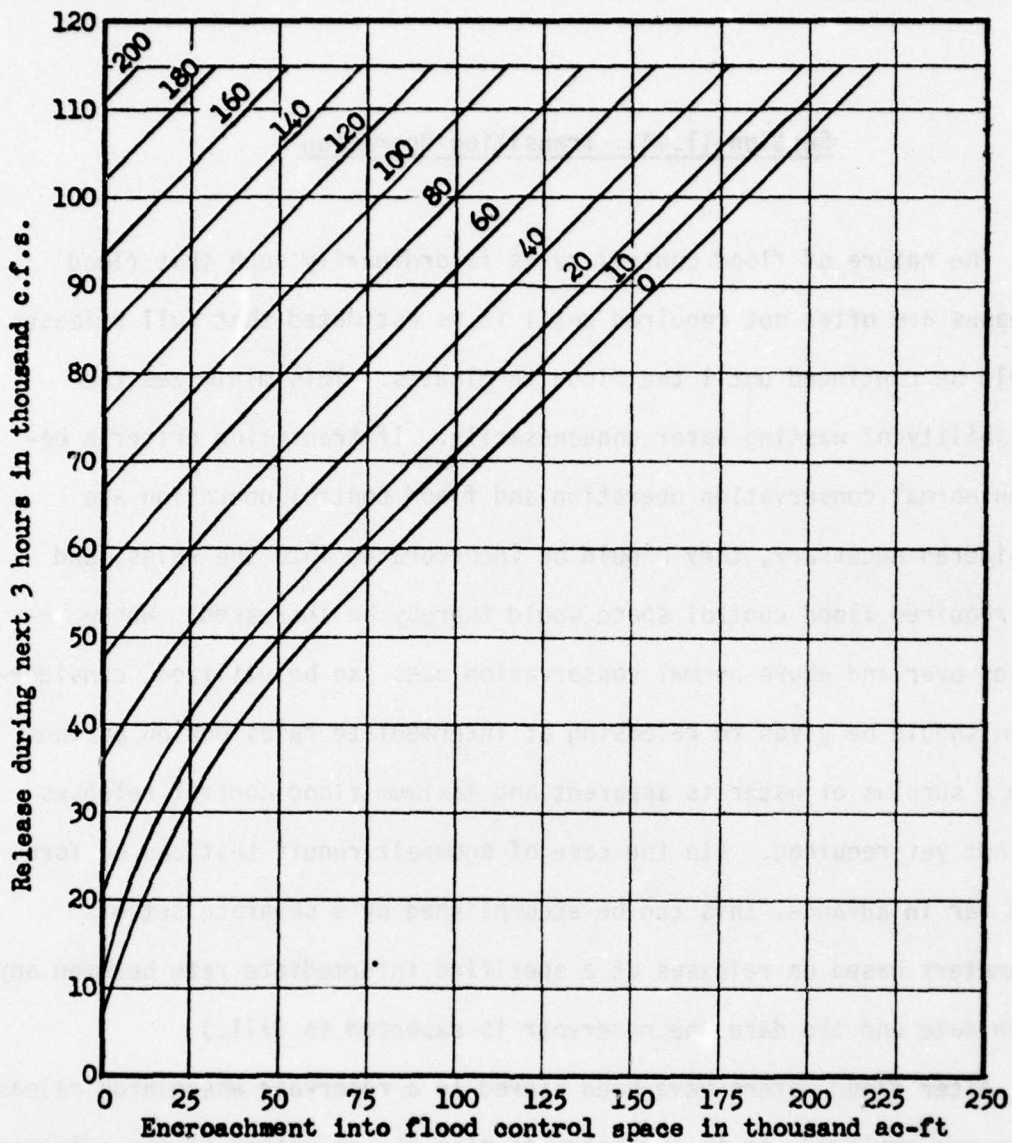
NOTES:
1. For use only when peak inflow is past or no large increase in inflow is anticipated.
2. Parameter values are current inflow in thousand c.f.s.
3. Do not change release more than 10,000 c.f.s. during any 2-hour period.

Fig. 11.01. Criteria for reduction of flood releases

of fall of preproject river stages after floods. For example, fig. 11.01 is based on the following schedule:

Range of release (cfs)	Rate of change of release per 3 hours	Rate of change of river stage (ft/3 hours)
5,000 - 25,000	5,000 cfs	2.2 - 1.2
25,000 - 60,000	6,000 cfs	1.4 - 1.1
60,000	10%	1.1 - 1.7

b. For selected periods of time prior to the time that releases are reduced to conservation rates, compute the volume of water that would be released in accordance with the adopted release reduction schedule (see column 3 of table 11.01.)

c. Select a rate of inflow recession which is somewhat less than the most rapid observed rate of inflow recession after floods. This is expressed as the time in days required for the flow to recede from a value Q to a value equal to Q/2.718, and is designated as T_S. The curves of fig. 11.01 are based on a value of T_S = .542 days.

d. The volume under a logarithmic recession curve during a period of t days after an initial inflow Q is given by the following equation:

$$V = 1.98 \, T_S \, Q \, (1 - e^{-t/T_S}) \qquad (11-1)$$

in which:

V = volume under the recession curve in acre-feet

T_S = the recession time constant in days (see c above)

Q = the initial inflow in c.f.s.

t = time in days after the initial inflow

Table 11.01

COMPUTATION OF RELEASE REDUCTION CRITERIA

(Volumes in thousand acre-feet)

Remaining hours of release	Release – Next 3 hrs in thous cfs	Release – Remaining Volume	Remaining inflow volume when current inflow (thousand cfs) is equal to:									
			20	40	60	80	100	120	140	160	180	200
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
48	115.0	219.4	21.0	41.9	62.9	83.8	104.8	125.8	146.7	167.7	188.6	209.6
45	105.5	190.9	20.8	41.6	62.5	83.3	104.1	124.9	145.7	166.6	187.4	208.2
42	93.1	165.2	20.6	41.3	61.9	82.6	103.2	123.8	144.5	165.1	185.8	
39	83.8	142.1	20.4	40.8	61.3	81.7	102.1	122.5	142.9	163.4		
36	75.4	121.3	20.1	40.3	60.4	80.6	100.7	120.8				
33	67.9	102.6	19.8	39.6	59.4	79.2	99.0	118.8				
30	61.1	85.8	19.4	38.7	58.1	77.4	96.8					
27	55.0	70.7	18.8	37.6	56.4	75.2						
24	49.0	57.0	18.1	36.2	54.3							
21	43.0	44.9	17.2	34.4	51.7							
18	37.0	34.2	16.1	32.2								
15	31.0	25.0	14.7	29.4								
12	25.0	17.4	12.9									
9	20.0	11.2	10.7									
6	15.0	6.2	7.9									
3	10.0	2.5										
0	7.5	0										

Remaining hours of release	Flood-control storage when current inflow (thousand cfs) is equal to:									
	20	40	60	80	100	120	140	160	180	200
(1)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
48	198.4	177.5	156.5	135.6	114.6	93.6	72.7	51.7	30.8	9.8
45	170.1	149.3	128.4	107.6	86.8	66.0	45.2	24.3	3.5	
42	144.6	123.9	103.3	82.6	62.0	41.4	20.7	0.1		
39	121.7	101.3	80.8	60.4	40.0	19.6				
36	101.2	81.0	60.9	40.7	20.6	0.5				
33	82.8	63.0	43.2	23.4	3.6					
30	66.4	47.1	27.7	8.4						
27	51.9	33.1	14.3							
24	38.9	20.8	2.7							
21	27.7	10.5								
18	18.1	2.0								
15	10.3									
12	4.5									
9	0.5									

Using this equation, compute the volume of inflow (V) for each of several assumed values of initial inflow (Q) and for values of t corresponding to periods of release given in column 1, table 11.01 (see columns 4 to 13, table 11.01.)

$\underline{f}$. For corresponding periods of time, subtract these inflow volumes from the release volumes (column 3 of table 11.01) to obtain values of flood control storage (see columns 14 to 23 of table 11.01).

$\underline{g}$. Release during the next 3 hours (column 2 of table 11.01) is plotted against flood control storage (columns 14 to 23, table 11.01) for each of the assumed values of initial inflow to obtain the curves of fig. 11.01. The parameter values of the curves are equal to the assumed initial inflow.

In using the curves constructed as described above, whenever the indicated release corresponding to the current inflow and current flood control storage is less than the current release, the release should be reduced to the indicated value. This process is repeated each interval (every 3 hours, in this case) until the release has been reduced to conservation rates. Fig. 11.02 illustrates the use of release-reduction criteria.

Section 11.05. Means of Compensating for Space Reduction

Whenever regulations provide less flood control space at any particular time than would be required for complete control of design rain floods with seasonal adjustment (in order to increase the overall accomplishments of the project), compensating changes in constructing the
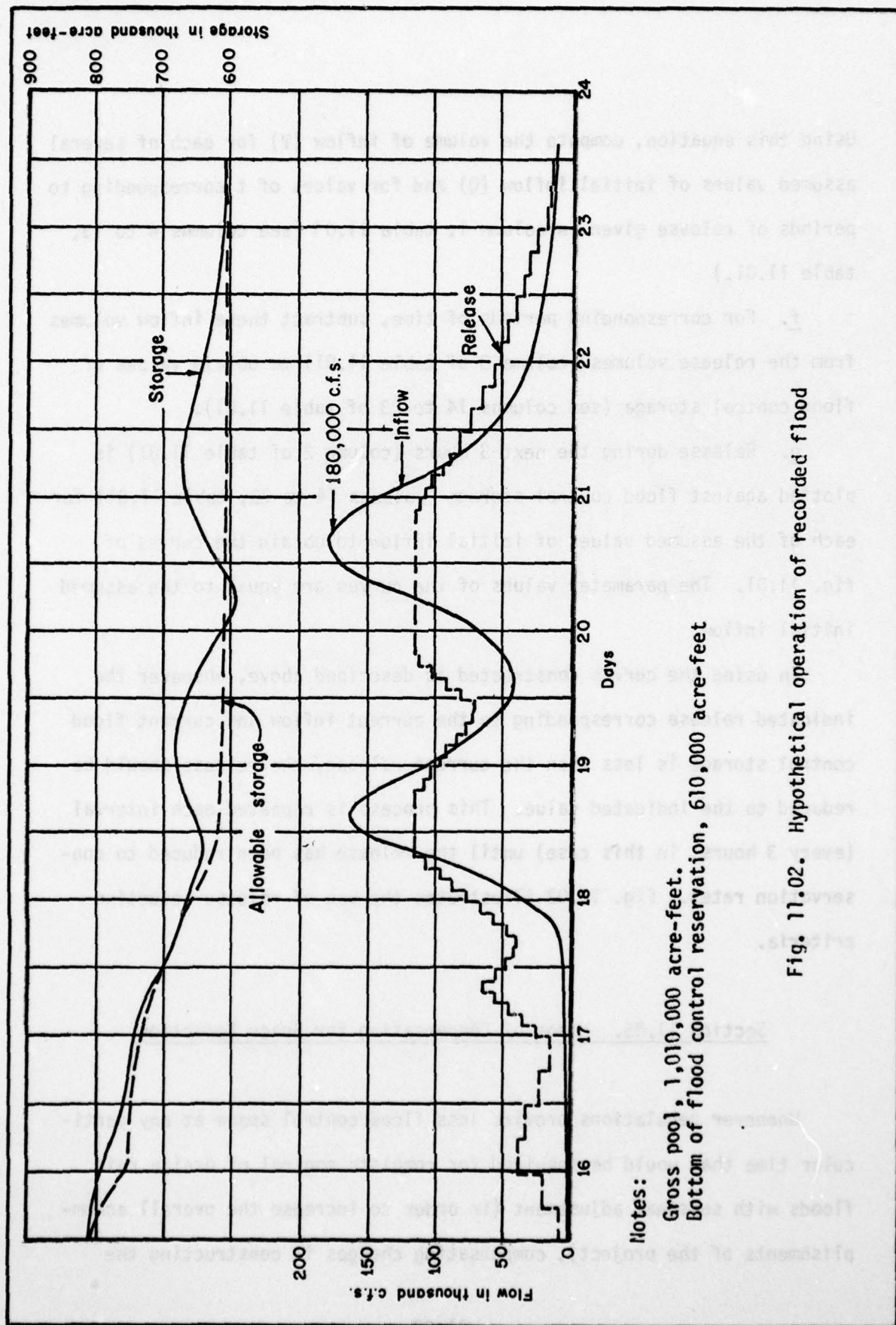
Fig. 11.02. Hypothetical operation of recorded flood

diagram should be made, if feasible, or benefits claimed for the control of floods should be correspondingly reduced. A suggested procedure is as follows:

_a_. Construct a flood control diagram in accordance with principles discussed above so that assured control of the project design storm or flood is obtained. It is recognized that the element of chance is considered in constructing flood control diagrams, but the diagram should be such that the difference between accomplishments with the diagram and accomplishments obtained by providing the maximum flood control space inviolate at all times is not greater than 5 percent and preferably in the order of 1 or 2 percent.

_b_. Reduce required space during the period in question by not more than one-third (i.e., allow reservoir to be drawn down by a later date or to begin filling on an earlier date, but provide at any date at least two-thirds of the space required on that date by the normal flood control criteria).

_c_. Increase all ordinates of empty space by a constant ratio so that the area of the flood control diagram is equal to the original corresponding area.

CHAPTER 12. USE OF COMPUTER PROGRAMS

Many of the computations needed for developing operation rules and criteria for flood control reservoirs can be accomplished by use of electronic computer programs contained in the various volumes of this report.

The computer program HEC-1, which is described in Appendix 1 of Volume 1, is capable of computing design floods and typical floods used for evaluating project accomplishments.

Computer program HEC-5C, which is described in detail in Appendix 1 of this volume, is intended for simulation of the sequential operation of a system of reservoirs of any configuration for short interval historical or synthetic floods or for long duration non-flood periods or for combinations of the two. The program may be used:

_a._ To determine flood control and conservation storage requirements of each reservoir in a system.

_b._ To determine the influence of a system of reservoirs on the spatial and temporal distribution of runoff in a basin.

_c._ To evaluate operational criteria for both flood control and conservation for a system of reservoirs.

_d._ To determine the average annual flood damages, system costs, and system net benefits for flood damage reduction.

_e._ To determine, by simulating selected alternative systems, the system of existing and proposed reservoirs or other alternatives, including nonstructural alternatives, that produces the maximum net benefits for flood control.

Reference 10 illustrates in considerable detail how HEC-5C can be
used to analyze structural and nonstructural flood control measures.

A program for computing the discharge capacity of outlets for various
openings of sluice gates is included as Appendix 2 of this volume and is
entitled "Conduit Rating - Partial Gate Openings."

A program for computing the discharge capacity of a spillway for
various openings of tainter gates is included as Appendix 3 of this
volume and is entitled "Spillway Rating - Partial Tainter Gate Openings."

The program "Spillway Rating and Flood Routing," which is designed
to facilitate the selection of spillway characteristics and to route
floods through spillways, is described in Appendix 4.

Appendix 5 contains a description of a program entitled "Spillway
Gate Regulation Curve," which performs most of the computations required
for the development of emergency release diagrams discussed in Chapter 6.

The techniques employed in all of the above computer programs and the
manner in which they are used are discussed in detail in the descriptions
constituting each Appendix.

SELECTED BIBLIOGRAPHY

1. Burnash, R. J. C., Ferral, R. L., and R. A. McGuire, "A Generalized Streamflow Simulation System-Conceptual Modeling for Digital Computers," Joint Federal-State River Forecast Center, Sacramento, California, March 1973.

2. Davis, C. V., ed., Handbook of Applied Hydraulics, 3rd ed., McGraw-Hill, 1969.

3. King, H. W. and Brater, E. F., Handbook of Hydraulics, 5th ed., McGraw-Hill, 1963.

4. U. S. Army Corps of Engineers, North Pacific Division, "Program Description and User Manual for Streamflow Synthesis and Reservoir Regulation SSARR," Portland, Oregon, September 1972.

5. U. S. Army Corps of Engineers, Office, Chief of Engineers, Hydraulic Design Criteria, prepared by the Waterways Experiment Station, Vicksburg, Mississippi.

6. U. S. Army Corps of Engineers, Office, Chief of Engineers, "Reservoir Regulation," EM 1110-2-3600, Washington D. C., 1959.

7. U. S. Army Corps of Engineers, Office, Chief of Engineers, "Routing of Floods Through River Channels," EM 1110-2-1408, Washington D. C., 1960.

8. U. S. Army Corps of Engineers, Office, Chief of Engineers, "Hydraulic Design of Reservoir Outlet Structures," EM 1110-2-1602, Washington D. C., 1963.

9. U. S. Army Corps of Engineers, Sacramento, California, "Reservoir Operation Criteria for Flood Control, Sacramento-San Joaquin Valley, California," October 1959.

10. U. S. Army Corps of Engineers, The Hydrologic Engineering Center, "Analysis of Structural and Nonstructural Flood Control Measures Using Computer Program HEC-5C," Training Document Number 7, April 1975.

11. U. S. Department of Commerce, National Weather Service, "National Weather Service River Forecast System Forecast Procedure," NOAA Technical Memorandum NWS-HYDRO-14, Washington D. C., 1972.
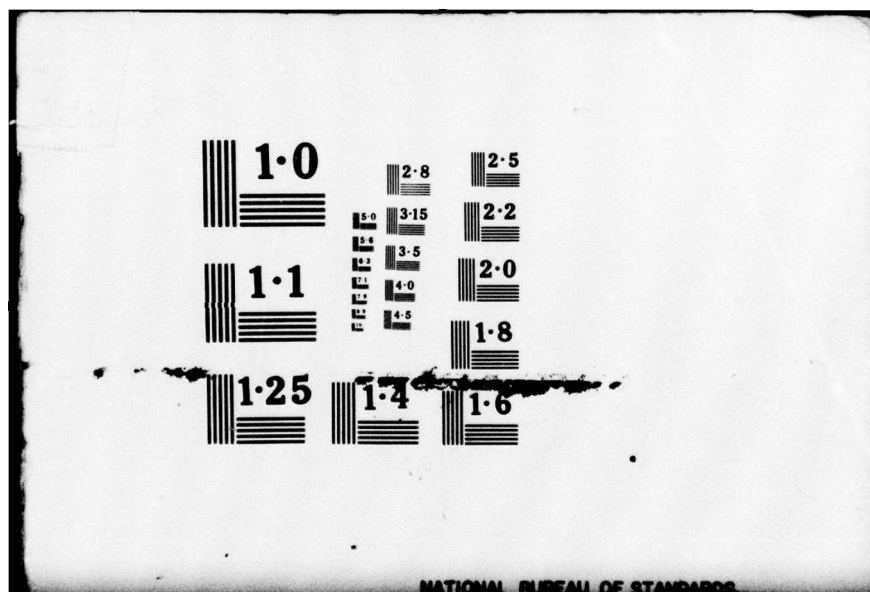
12. United Nations and World Meteorological Organization, "Methods of Hydrological Forecasting for the Utilization of Water Resources," Transactions of the Inter-Regional Seminar on Methods of Hydrological Forecasting for the Utilization of Water Resources, held at Bangkok, Thailand, 4-17 August 1964, Water Resources Series No. 27, United Nations Publication.

GLOSSARY

1. RESERVOIR POOL ELEVATIONS.

    a. References to reservoir pool "level" or "elevation" apply to water surface elevations in the reservoir near the dam site, exclusive of wave action and wind-tide effects.

    b. Normal Full Pool Elevation: This term corresponds to the top reservoir level that would be attained for routine storage of water for flood control, hydroelectric power, low-flow augmentation, recreation, sediment control, or other authorized storage uses; this level corresponds to the "total design capacity" of the reservoir selected initially on the basis of planning and design studies, excluding surcharge storage that is provided primarily to reduce costs of constructing and maintaining the dam and appurtenances or to improve safety of operation during emergencies.

    c. Surcharge Pool Elevation: Any accumulation of storage above the "Normal Full Pool Elevation" is referred to as "surcharge". The highest surcharge pool level attained during the passage of a particular flood is referred to as the "Maximum Surcharge Elevation" for that flood. Inasmuch as the accumulation of surcharge storage during a particular flood is dependent upon the plan of reservoir operation adhered to, and the initial pool level, these should be identified with any designation of maximum surcharge elevation.

    d. Induced Surcharge Elevation: The accumulation of surcharge storage above the normal full pool level during a particular flood may

be "induced", entirely or in part, by operating the regulating out-lets and/or spillway gates at partial openings. Such operations can serve to reduce peak reservoir outflow rates and/or permit a more gradual increase in downstream river stages, while higher surcharge elevations are caused in the reservoir. Although induced surcharge may be utilized to obtain additional flood control effectiveness or safer operation of a project in some cases, the storage space used is not identified as primary flood control capacity and does not affect the designation of the "Normal Full Pool Elevation", as pre-viously defined.

e. <u>Storage Rule Curve Elevations</u>: In multiple-purpose reser-voirs, it is common practice to establish elevation guide lines to govern the accumulation and drawdown of storage for various uses, with appropriate variations by seasons to conform with functional needs and runoff probabilities. For example, a "rule curve" or "guide line" may permit a relatively high reservoir level to be maintained for the benefit of hydroelectric power development during seasons of the year when flood problems are a minimum, and require drawdown to lower levels to provide greater storage space for flood control as the most severe flood season approaches. When it is necessary to store water above the "power pool rule curve" in order to control floods, such storage would normally be evacuated as promptly as possi-ble without adding to downstream flood conditions, making releases not only through the power turbines but also through flood control outlets if necessary; in some cases, evacuation of storage above the power rule curve may be delayed to avoid or reduce wasting of water,

if flood forecasts or probability analyses warrant such action. Elevation rule curves are also used to govern seasonal changes in recreation pool levels, storage accumulations and drawdown for water supply, low-flow augmentation, and other multiple-purpose reservoir storage uses. These rule curves, established on the bases of economic studies and hypothetical reservoir operation and analyses usually have an important bearing on project design requirements.

f. _Inactive Pool Elevation_: Refers to the lowest elevation to which a reservoir would be drawn to attain primary project design objectives. Any releases made when the pool is below this level normally would be the minimum required to meet legal requirements or emergency provisions.

g. _Dead Storage Elevation_: The lowest elevation at which it is practicable to release water from the reservoir, as governed by design of outlet facilities.

2. RESERVOIR STORAGE SPACE CATEGORIES.

a. Unless otherwise indicated, references to "storage space" correspond to the reservoir capacity available between two flat pool elevations as indicated by appropriate elevation-capacity curves.

b. _Sediment Storage Capacity Allowances_: Refers to storage space allowance provided for deposition of sediment within reservoir limits during the assumed life of the project. If the sediment accumulation expected is so small as to have a relatively small effect in depleting storage required for primary reservoir functions, allowances for sediment are usually included as a part of the "inactive

storage" capacity; otherwise, special studies are required to establish acceptable estimates of amounts that various storage use allocations will be affected by sediment depositions.

    c. <u>Inactive Storage Capacity</u>: Includes the gross capacity below the "inactive storage elevation."

    d. <u>Drawdown Storage Capacities</u>: Refers to storage space reserved for impoundment of runoff during some periods for the express purpose of retaining the water for later release when needed for industrial and municipal water supplies, irrigation, hydroelectric power generation, water quality improvement downstream, enhancement of downstream navigation, and other water uses. The same drawdown storage space may serve several of the water use objectives referred to, provided the total space is large enough to regulate flows within acceptable provisions of scheduling; in such cases, the drawdown storage space is referred to as a "joint use" pool, further designated by design purposes involved.

    e. <u>Primary Flood Control Storage Capacity</u>: Refers to any storage space below the "Normal Full Pool Elevation" in which storage runoff and subsequent releases therefrom are made, with control of downstream floods as a primary objective. The primary flood control storage capacity reserved in a reservoir may be varied on a fixed rule curve basis to provide the largest capacity during seasons when flood control needs are greatest.

    f. <u>Joint Use Flood Control Storage Capacity</u>: Refers to storage capacity that is made available for flood control use on a flood-runoff forecast basis, and/or with certain limitations on use in

conjunction with some other storage function, such as hydroelectric power or irrigation. The term does not apply to "incidental" flood control use of storage that is not governed by specific rules to assure availability of the storage space according to conditions established prior to the flood occurence.

3. SPILLWAY.

In broad terms, a "spillway" may be defined as any passageway, channel, or structure designed expressly or primarily to discharge "excess" water from a reservoir after the design storage capacity and design discharge capacities of regulating outlets, turbines, and other project facilities have been used to perform normal operating functions.

4. REGULATING OUTLETS.

In design studies it is usually desirable to distinguish between "regulating outlets" provided primarily for routine operation of a reservoir and "spillway" facilities intended primarily for use in discharging excess waters, inasmuch as many different design considerations are involved. However, regulating outlets and spillways usually are complementary structures. A variety of combinations have been adopted to conform with various functional needs and design advantages. Under some circumstances, regulating outlets are inoperable during severe floods because of lack of access to operating towers, or because heads exceed those for which the outlets were designed. On the other hand, some regulating outlets that are provided

primarily to serve routine operating functions, before the design storage capacity of the reservoir is exceeded, are also designed to discharge "excess" waters when required, usually with the objective of reducing the frequency of emergency or limited-service spillway operations; such a structure may be designated as a "service spillway", if the capacity to discharge excess waters is a major portion of its total capacity. In contrast, some spillways are used regularly or occasionally to make routine reservoir releases associated with flood control operations or to augment downstream flows for navigation, pollution control, or other purposes.

5. CONTROLLED AND UNCONTROLLED SPILLWAYS.

Many types and plans of controlled and uncontrolled spillways are used to conform with advantages and requirements of various dam and reservoir sites. A spillway is designated as an "uncontrolled" type when there are no gates, stoplogs, or other means of preventing free overflow when the reservoir exceeds the crest elevation; the terms "ungated" or "free overflow" are commonly used in the same sense. A "controlled" spillway type is equipped with crest gates, stoplogs, or other movable structures to permit various degrees of variation in outflow rates when reservoir levels exceed the spillway crest elevation; the term "gated" is usually supplemented with information to identify the structural or mechanical type of gate involved.

6. STANDARD PROJECT FLOOD (SPF).

The SPF hydrograph represents critical concentrations of runoff from the most severe combination of precipitation (and snowmelt, if pertinent) that is considered "reasonably characteristic" of the drainage basin involved. The SPF peak discharge and volume is usually equal to about 40% to 60% of the PMF estimate for the same drainage basin, when the comparison is related to rainfall concentrated in approximately 4 days or less. In studies involving reservoirs in which storage effects are important, the SPF derived from relatively short period rainfall (4 days or less) is usually assumed to follow a period of substantial flood runoff, the combination being referred to as the "SPF Series."

7. PROBABLE MAXIMUM FLOOD (PMF).

This term identifies estimates of hypothetical flood character- istics (peak discharge, volume and hydrograph shape) that are consi- dered to be the most severe "reasonably possible" at a particular location, based on relatively comprehensive hydrometeorological analyses of critical runoff-producing precipitation (and snowmelt, if pertinent) and hydrologic factors favorable for maximum flood runoff.

8. SPILLWAY DESIGN FLOOD (SDF).

This term refers to the reservoir inflow-discharge hydrograph used in estimating the maximum spillway discharge capacity and maxi- mum surcharge elevation finally adopted as a basis for project design assuming the initial reservoir pool elevation and general plan of

water releases (through the spillway, regulating outlets, hydro-power turbines and other outflow facilities) specified in the reservoir regulation plan established for use under critically severe flood conditions. The spillway design flood estimate for a particular project may conform with the PMF, the SPF, or some other magnitude of flood, depending upon the degree of hazard that might result from overtopping of the dam.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HEC-IHD-0700	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Hydrologic Engineering Methods for Water Resources Development. Volume 7, Flood Control By Reservoirs.		5. TYPE OF REPORT & PERIOD COVERED Final rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Leo R. Beard		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Hydrologic Engineering Center Corps of Engineers, U. S. Army 609 Second Street, Davis, California 95616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Feb 76
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Corps of Engineers Washington, D. C.		12. REPORT DATE June 1975
		13. NUMBER OF PAGES 451 124 P.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this document is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

International Hydrological Decade
Flood Control
Reservoir Operation
Rule Curves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is Volume 7 of a 12-volume report prepared by The Hydrologic Engineering Center as a part of the U. S. Army Corps of Engineers' contribution to the International Hydrological Decade. Basic principles of reservoir operation for flood control are presented and procedures for establishing operational criteria are described. Topics include determination of reservoir release rates, regulation of the reservoir design flood, considerations for determining outlet →

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

407 989

and spillway regulation, determination of rule curves, and procedures for analyzing multiple-reservoir operation. The applicability of computer simulation for establishing operational criteria is discussed and several computer programs are described in the appendixes.

HYDROLOGIC ENGINEERING METHODS FOR WATER RESOURCES DEVELOPMENT